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THE FUNDAMENTAL PRINCIPLES OF PETROLOGY

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THE FUNDAMENTAL PRINCIPLES OF PETROLOGY

BY

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AUTHORIZED TRANSLATION
(FROM THE THIRD GERMAN EDITION)

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WITH 137 FIGURES AND 6 PLATES

FIRST EDITION

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To the Memory
of
Caroline Austin Duror
this Translation
is Dedicated

TRANSLATOR'S PREFACE

The need of a short presentation of the fundamental principles of petrology as applied to geology has suggested the translation of the first volume of Professor Weinschenk's *Grundzüge der Gesteinskunde*. Without thereby expressing his belief or disbelief in the views of the author, the translator has tried to adhere as closely as possible to the sense as well as to the mode of expression of the original. Only in the case of the Osann classification has any additional material been inserted. The rules for calculating analyses in this system are readily accessible to the German student but not to others, and in view of the growing use made of Osann's triangular diagrams by European geologists, the addition was thought justifiable. Owing to the uncertainty of shipments from Germany, it was impossible to obtain the original electrotypes of the illustrations, consequently the cuts in this translation were reproduced from the figures in the German volume, and are not quite so sharp as they otherwise would have been.

The translator is deeply indebted and very grateful to Dr. E. A. Stephenson for critically reading this manuscript and for various suggestions. He is also indebted to Miss Caroline A. Duror for carefully reading it and for pointing out certain ambiguous passages. The sad death of this brilliant and promising student permits the writer to express his appreciation only in the dedication of this translation to her memory.

ALBERT JOHANNSEN.

THE UNIVERSITY OF CHICAGO,
August 14, 1916.

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THE FUNDAMENTAL PRINCIPLES OF PETROLOGY

INTRODUCTION

Petrology, or the study of rocks, treats of the origin, present condition, and decay of rocks. It traces their history through every stage of their existence, and contributes to our knowledge of the processes by which the earth has been brought to its present state. Thus defined, petrology is one of the most important fundamentals of geology, yet it has been greatly neglected by past and present workers in the science. A geologist, justly, is expected to have a thorough training in paleontology, for without it successful geologic work is impossible. But the requirement of proper paleontologic preparation has led to a one-sided treatment of the subject, the petrologic side remaining undeveloped.

No one who is interested in unraveling the geology of a region will find fault with a field geologist for having the most complete knowledge possible of things paleontologic, but such knowledge does not justify him in neglecting the assistance offered by petrology; knowledge especially indispensable to the working geologist. Whoever would comprehend all the phases of geology must give petrology the same weight as paleontology, and draw upon each equally for his results.

The causes which led to the great preference given to paleontology cannot be discussed here in detail. Broadly speaking, they depend upon the fact that when paleontology started, all preliminaries for rapid growth were found in the high stage of development of zoology, and with this for a starting point, it needed but to grow. Its methods of research, also, were relatively simple, and did not first require apparatus and instruments of many kinds. Thus, spreading over a prepared field, it captured the spirit of the investigator by its surprising and easily reached results.

Petrography did not find such a road before it. Step by step it had to prepare its own path; it advanced slowly, and was continually repulsed by many obstacles, until finally the introduction of the microscope raised it to equal rank with the other sciences. But with the introduction of microscopic methods a peculiar change took place. While formerly none but geologists made use of petrographic-research methods, and these necessarily of the simplest and most elementary kinds, an entirely new trend now came about. Rocks were examined simply to determine their mineral components, and no attention was paid to their geologic relationships. Thus there arose a school, purely mineralogic and entirely independent of geology, whose viewpoint extended but little beyond the walls of the laboratory or beyond the field of the microscope, and only rarely did a practical geologist dare to enter the sacred precincts of microscopic petrography. The unsuspected wonders then first revealed in the rocks, completely fascinated those who had overcome the many difficulties of the preliminary training necessary for microscopic petrography; yet on account of their deficient geologic training, few petrographers could solve geologic problems. Paleontology, on the other hand, gave an abundance of important results.

The purely mineralogic tendency did not persist a great while, for petrographers soon realized that geologic research was as necessary as microscopic observation. Geologists, however, had become accustomed to the idea that this science was a hothouse production which could not bear transplanting, and even at the present time a large number of geologists regard with suspicion, if not with direct distrust, the results obtained by petrographic research; and this aversion, instead of diminishing, increases more and more as petrologists continue to destroy theories which had been considered fundamentals of geology. The results of modern petrographic research, however, are of such great importance to geology that the attempt on the part of many geologists to exclude them is an injury to their science.

At the present time, petrography does not concern itself simply with the microscopic examination of thin sections. Its horizon has been broadened, and the greater as well as the lesser features of the rocks have become the subject of its study. The microscopic object, certainly, even yet remains an important working tool of the craft, but observations in the field and the study of the

geologic relationships of the rocks to each other have become of just as great importance. While the great museums formerly hesitated to allot even a little dark corner to petrographic collections, at the present time the rocks are given a place of equal rank with other collections. Rock specimens which show the broad geologic relationships are now valued most, and instead of being tiresome, side-by-side arrangements of hand-specimens of uniform size, these collections have come to rank among those that are most stimulating.

Petrography, as the youngest branch of geology, is still far from the stage where practically everyone holds the same views; a stage which has been reached to such a great extent, at least apparently, by the other branches of the science. Nevertheless, geologists cannot afford to be antagonistic to the results of its investigations, although this is the attitude taken by the authors of some of the most recent geologic text-books.

It is a fact not to be overlooked that the student must have had a broad preliminary training to reach the desired goal in petrography; a training which generally takes more time and effort than he is willing to give to a subject which he considers simply a subordinate aid. For this reason it has been customary for the instructor in geology to present to his students, as sufficient for their purpose, only those facts which were known before true petrography existed, and then to console himself, and excuse his own superior attitude toward the whole science, by reflecting that the numerous rock-types, which over-specializing petrographers have set up, have neither geologic significance nor justification; that the new names which arise in such rapid succession have the ephemeral character of day-flies; and that even among petrographers who have made the science their life-work, but little unanimity yet exists in regard to the most important questions affecting geology. But what science has become great without having had its truths promoted by opposition to its accepted views, and in what science have the subdivisions of the classification and the setting up of new names grown to such proportions as in paleontology, which, in spite of this, is in such high favor with geologists?

The attempt here made to give a history of the rocks from the standpoint of modern petrography, primarily for geologists, may appear a somewhat thankless task. The presentation of the most important results of petrographic research will encounter the

objection from the geologic side that their value to geologists is out of proportion to the difficulty with which the beginner can grasp and observe them, while on the other hand, the same presentation will be too generalized and too limited for the specialist in petrography.

I. DEFINITIONS AND SUBDIVISIONS

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Rocks may be defined as mineral aggregates which, with more or less constant composition, form geologically independent bodies and an essential part of the earth's crust.

Nearly all rocks are aggregates of different minerals, that is, rocks are *compound* or *mixed*. In the strict sense of the word, *simple* rocks, which consist of but a single mineral, are extremely rare. Mineral combinations, such as ore deposits, are not classified as rocks on account of their usual subordinate development and their less constant composition, although they possess the former property in common with numerous dikes. There is no sharp line of separation. Thus dark mica may not occur in the apophyses from some granites, yet these *aplites* are still regarded as rocks. The differentiation may have gone still farther; the feldspar also may have disappeared, and the vein-filling may consist almost exclusively of compact quartz. In spite of the absolute identity in the mode of occurrence of the aplite and the quartz, the latter is regarded rather as a mineral vein than a rock.

The constituents of a rock may have crystallized in the place in which they occur. Such aggregates of *authigenic* (Gr. αὐθι, on the spot, and γίγνομαι, to be born) individuals are called *crystalline* rocks. On the other hand, those rocks whose *allothigenic* (Gr. ἀλλοθι, elsewhere) components were derived from previously existing rocks, which were shattered and destroyed and later deposited elsewhere in secondary beds, are called *clastic* (Gr. κλαστός, broken) or *fragmental* rocks.

Certain rocks, namely the fluids and gases of the *hydrosphere* (Gr. ὕδωρ, water, σφαῖρα, sphere) and *atmosphere* (Gr. ἀτμος, vapor) which surround the solid part of the *lithosphere* (Gr. λίθος, stone) are neither crystalline nor clastic. Even some of the

FIG. 1.—Massive granite, Grimselstrasse. (Gebr. Wehrli, Photo.)

rocks occurring as solid aggregates do not belong to these two great groups, since they are built up of amorphous constituents formed *in situ*. Here belong the *glassy* or *hyaline* (Gr. ὕαλος, glass) volcanic rocks, such as obsidian and pitchstone, and the amorphous *porodine* (Gr. πόρος, pore, passage, δινειν, whirling) deposits from aqueous solutions, the so-called colloidal *gels*. The latter are so subordinate, however, that they would hardly be classed as rocks.

Crystalline rocks originated in various ways. If a primary crust solidified over the earth, it must necessarily have had a crystalline character. Molten masses, upon emerging from the interior of the earth, crystallize; aqueous solutions not infrequently give crystalline precipitates; and the action of igneous masses on originally clastic formations may produce crystalline aggregates. It is, consequently, not possible to use crystallinity as a basis for petrographic classification. It has been customary

instead, to divide the rocks according to their mode of origin. On this basis, three groups are distinguished.

(*a*) *Igneous* (Lat. *ignis*, fire) or *eruptive* (Lat. *erumpere*, to break forth) rocks embrace those masses which were forced upward in a molten condition from within the earth, and therefore also called *anogenic* (Gr. ἀνω, upward), or from their usual external appearance, *massive* rocks (Fig. 1). They are authigenic or primary, and are typical of the majority of crystalline rocks.

(*b*) *Sedimentary* (Lat. *sedere*, to settle) rocks include all rocks which originated by precipitation from circulating surface water, and all rocks whose components, transported by any means what-

FIG. 2.—Stratified limestone near Wiesbaden. (Prof. Dr. Klemm, Photo.)

ever, were deposited from above. They are also called *catogenic* (Gr. κατά, down from) or, from their usual character, *bedded* rocks (Fig. 2). The sediments are secondary and consist essentially of allothigenic constituents. They are types of clastic or fragmental rocks.

(*c*) The *crystalline schists*, finally, whose characteristic representatives were supposed to belong to the oldest formation of the earth, the so-called Archean (Gr. αρχαῖος, ancient) or Azoic (Gr. α, without, ζωή, life), form a group whose genetic relationships are in many cases uncertain. They are therefore also called *cryptogenic* (Gr. κρυπτος, hidden) rocks. They consist, on the whole, predominantly of authigenic constituents, and are in part primary and in part secondary rocks; the latter are usually much altered.

Only the outermost beds of the earth's crust are known, the deepest openings being less than one two-thousandth of the earth's radius. That which lies below is entirely inaccessible, and we can only conjecture as to its condition.

The temperature of the earth increases with depth in the outer, accessible parts, and while the temperature gradient differs greatly in different places, it averages about 30° per kilometer. Assuming a uniform increase from the surface downward, the center would have a temperature of about 200,000°, the earth's radius being more than 6,000 km. There is no proof that this increase in temperature is uniform to the center of the earth, since only a small percentage of the whole is known, but the assumption that the interior has a high temperature is not unjustifiable.

We know, further, that the specific gravity of the earth as a whole is about 5.5, or about twice as much as the average density of the accessible portion of the crust. Within the interior, therefore, there must be present a great abundance of very heavy minerals, most probably native iron, a constituent which also forms an important part of meteorites, themselves fragments of destroyed worlds.

Further, the pressure in the interior must be enormously greater than at the surface, whereby the molecules, in the highly heated, presumably gaseous masses, must be so closely packed that the gas does not occupy so large a volume as would the same material in the solid state under less pressure. As a necessary consequence, enormously greater stresses must exist in the interior than in the crust.

II. THE SOLIDIFIED CRUST AND THE CRYSTALLINE SCHISTS

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The Formation of the Earth's Crust. If we wish to familiarize ourselves with the processes by which the rocks were formed, we must study the earlier phases of the history of our solar system when the earth, perhaps, was in the form of a molten mass surrounded by a thick gaseous mantle. After a long period of time the temperature of the surface may have been reduced so far that a solid crust was formed over the molten interior; a crust which was not scoriaceous like the upper surface of a lava-stream, but uniformly crystalline like granite, on account of the extreme slowness of the cooling and the enormous pressure of the heavy atmosphere.

During this period, the temperature of the earth's surface was much above the critical temperature of water, and the present ocean, then existing as vapor, formed the chief constituent of the gaseous envelope. The atmospheric pressure, for this reason alone, had risen to over two hundred atmospheres. In addition there were innumerable other substances, gaseous at such high temperatures, and their combined weight produced a pressure at the sur-

face such as is reached only deep within the earth at the present time. By these means the molten masses became saturated with many kinds of gases and vapors; the influence of which, as mineralizers, will be described later.

Not only were the outer parts of the molten earth overloaded with water-vapor and other gaseous substances, but they were present in excess even to its innermost parts. The enormous stresses produced by these gases, heated much above their critical temperatures, counterbalanced the enormous pressure of the atmosphere. In this manner the first coat of armor for the young earth was formed, not uniformly and continuously, but often disturbed by immense eruptions, often torn by molten masses gushing forth from the deeps. As to how long the alternations of solidification and fragmentation lasted, who would venture a guess! As time passed the fluid center was more and more firmly imprisoned by the solid shell, until finally the temperature of the outer portion of the crust was reduced below the critical temperature of water. The vapors then for the first time descended as boiling rain upon the mantle built by volcanic forces.

The water, which became fluid under such high pressure at 365°, was exceptionally active chemically, especially toward the silicates, and dissolved and re-worked the outer parts of the earth's crust. It soon became saturated with all possible substances, in part removed from the atmosphere, in part derived from the solidified crust. Thus there came to cover the earth's surface, as yet unwrinkled and unfractured, a peculiar, universal sea, purely chemical in its activity, differing widely in composition from our present ocean, breaking on no coast, and receiving detrital materials from no stream.

The stresses in the interior probably even yet often rent the weak crust; great volcanic masses gushed forth and were mingled with the supersaturated aqueous solutions of the primeval sea. The solidified crust itself became covered with rocks combining in themselves the characters of precipitates and of volcanic formations. The temperature decreased more and more, and the crust became thicker and thicker by the continued cooling of the interior and by the addition of erupted masses and precipitates on the surface, until finally the exterior of the earth was not very different from what it is at present. As the temperature decreased, the water lost a great part of its chemical activity. The thickening

crust permitted fewer and fewer fractures, and instead of the continual small eruptions of the first stage, there were occasional great eruptions which sent forth enormous flows. Thus were formed the first wrinkles and furrows on the surface, the first elevations and depressions; the land was separated from the sea! The waters now began to erode and level the still but slightly elevated land. In place of the chemical sediments, probably chiefly silicic, of the earlier periods, there were now formed deposits predominantly mechanical, made up of fragments of older rocks.

With this change in the character of the sedimentation, the earth's surface soon became habitable for organisms, and the stage of formation of the oldest clastic and fossil-bearing sediments was reached.

Characteristics of the Crystalline Schists.—If the geologic column is traced downward, there will be found, finally, in every part of the earth, a zone in which the rocks are universally and strikingly different in character. The fossiliferous beds, from the youngest Cenozoic to the oldest Paleozoic, show no fundamental petrographic differences except that the oldest rocks usually, but not always, are more firmly consolidated than the younger. Below these sediments, however, a general crystalline character suddenly appears, almost invariably accompanied by an absence of fossils. These lowest deposits have generally been regarded as the oldest formation, and are known as the crystalline schists.

These crystalline schists, in certain localities, are unconformably overlaid by the later sediments. In other places there is no sharp boundary between the two, and the crystalline formation passes by imperceptible transitions into the non-crystalline. The different members of this old series of crystalline schists are, in general, the same everywhere, and consist of gneisses, mica-schists, and phyllites.

Beneath the fossiliferous formations, then, the crystalline schists are universally present. They possess, on the whole, certain similarities, such as must necessarily have been produced in rocks deposited during the earliest stages of the crust's development. Everywhere, upon approaching the sedimentary and fossiliferous formations, there may be recognized a gradual decrease in the crystalline character, such as one would naturally expect with the gradual diminution in chemical activity presupposed during these primeval times.

A detailed examination of the crystalline schists, however, will show that the relationships are not so simple as they appeared at first sight, and that the above conclusions as to the origin of the crystalline schists is not justified.

Unquestionably a universal crystalline schist formation, consisting of gneisses, mica-schists, and phyllites, exists in all parts of the earth beneath the fossiliferous beds. But in many places the normal, typically developed rocks of the crystalline schist formation grade by unmistakable, gradual transitions into younger instead of into the oldest known sedimentary formations, and widespread formations of exactly the same petrographic characters as the crystalline schists are shown by their fossils to be of more recent geologic age. These formations have been called the *younger crystalline schists*, in an attempt to separate them from those considered to be truly Archean.

These young, even very young, crystalline schists are widely distributed, and their origin must be ascribed to causes different from those assumed for the older formations, since the condition of the earth's surface and of the atmosphere had long since been so fundamentally altered that a return to chemical sedimentation cannot be considered. Further, isolated areas of crystalline schists containing well-determinable fossils were already known at the beginning of the last century, and later research has led to the discovery of many more. In considering fossil evidence of this kind, all inorganic forms, such as Eozoon (cf. Part IX), formerly incorrectly thought to be organic, must naturally be disregarded. All of the definitely determinable fossils found in the crystalline schists are of organisms which are well known elsewhere, mostly as type fossils of more recent formations, and none of these fossils suggests an especially primitive form of life. This is all the more remarkable since the fossils actually present are not exclusively the more durable forms, but many of them, such as graptolites and plant remains, are especially perishable.

There were sediments, without doubt, much older than the crystalline schists, although the latter generally have been considered the oldest. In South Africa, for example, a whole series of unconformable systems, with individual members separated by erosion surfaces and transgressions, underlies known Silurian or Cambrian beds. While these strata have preserved their purely clastic characters, nowhere within them are any fossils found to serve as criteria for determining their age. It is noteworthy that these primeval strata are exposed in but few places upon the earth's surface, and that, even in South Africa, they are underlaid by gneiss-like rocks.

The fact that these massive, undoubtedly pre-Cambrian sediments do not occur elsewhere between the so-called Archean crystalline schist formation and the overlying normal sediments, led to the conclusion that they had been destroyed or thoroughly metamorphosed in some way during early Cambrian times, perhaps by great fissure eruptions. Since the pre-Cambrian sediments in South Africa are entirely without fossils, the corresponding metamorphosed rocks naturally cannot be expected to contain them. Furthermore, in the few places where lower or pre-Cambrian sediments are fossiliferous, for example in New Brunswick, the preserved forms are found to have very durable parts.

The petrographic characters of the crystalline schists are still less suggestive of primeval rocks, for although the different members recur everywhere as gneisses, mica-schists, and phyllites, moderately careful observation in different parts of the earth shows that the only characteristic common to all is their variability. Not only does the habit change from stratum to stratum, but the equivalent formations in different localities show but little analogy petrographically. Neither the gneiss,

mica-schist, nor phyllite forms a single unit in the petrographic sense. Since it must be presupposed that uniform conditions existed everywhere on the earth's surface during the deposition of the primeval sediments, the rocks should be uniform. As a matter of fact, the schists are characterized preëminently by their great lack of uniformity. If the so-called Archean formation in various regions is closely examined from a petrographic point of view, these differences will stand out sharply. There is, for example, hardly a rock-type in the crystalline central chain of the Alps which has its equivalent in the surrounding province of crystalline schists, and even in different parts of the central chain itself, the continual change in the development, formation, and composition of the crystalline schists is readily visible.

Crystallinity and great geologic age do not necessarily belong together, and the crystalline schists certainly do not occupy the definite position in the geologic column assigned to them by some geologists. None of the schists whose age is determinable belongs among the oldest strata of the earth, and it is not at all probable that many of the remainder have this great age. The crystalline character of rocks, in many cases, is only a secondary property developed by later alteration processes, namely by metamorphism (Gr. *μετὰ, μορφή. μεταμορφόομαι,* to be transformed).

When the appearance of a rock is due to later metamorphism, all conclusions as to the original process of formation, drawn from this obviously secondary characteristic, are necessarily incorrect. Petrographic investigation of the crystalline schists has shown the following fundamental principle of petrology to be correct: *The petrographic characteristics of a rock have no relation whatever to its geologic age.*

The earliest sediments must have had a uniform character, for they were derived from and deposited upon a universal, uniform, preëxisting crust, and while it is probable that the oldest deposits resembled certain of the crystalline schists in many ways, yet the latter do not possess the necessary homogeneity. From our present petrographic knowledge we can consider it only very improbable that the true, primitive crust is accessible anywhere upon the earth's surface.

III. VULCANISM AND THE ORIGIN OF IGNEOUS ROCKS

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Older Theories of Vulcanism.—The Kant-Laplace theory of the origin of the solar system is here assumed to be correct, since under it the phenomena of vulcanism are most easily explained.[1]

Among the older theories of vulcanism is that of Werner, who supposed that the subterranean burning of coal was the cause of the igneous activity. Other writers explained it as due to the oxidation of pyrite, alkali metals, etc., or, in more recent times, to the hydrolysis of carbides, but all of these theories have been abandoned.

From the existing average temperature gradient of 30° per kilometer, it might be assumed that at a depth of 40 to 50 km. all rocks are in a molten condition. On this assumption the thickness of the solid crust of the earth would be less than 1 per cent. of the radius, a proportion shown by the solid line in Fig. 3. In this case the earth's crust would be extremely thin and in the first stages of cooling, and a fluid or even partly gaseous interior would make up the greater part of the earth's mass. It has

[1] The translator wishes to call attention to the more probable method of origin suggested by Professors Chamberlin and Moulton. See Chamberlin and Salisbury: "Geology," 3 vols., New York, 2d edition, 1907.

even been asserted that the central portion of the earth, in spite of its enormous temperature, is in a solid state, since crystalline rocks occupy a smaller volume than their corresponding melts. A solid center is doubtful, however, for the critical temperature at which most of the substances in the earth's interior would assume a fluid condition under all circumstances would probably be reached at comparative shallow depths.

Most volcanoes which are active or were so during the latest geologic periods occur near seacoasts, and they are especially widespread on islands. Further, extrusive lavas give off more or less vapor, primarily water-vapor, accompanied by alkali chlorides, sulphates, etc., all of them characteristic constituents of sea

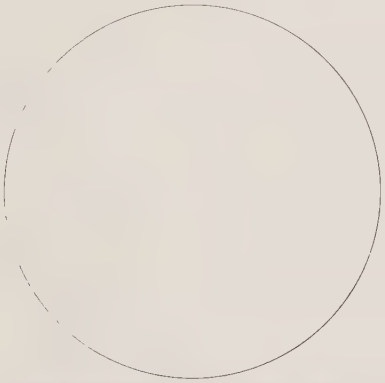

FIG. 3.— A crust 50 km. in thickness as compared with the diameter of the earth.

water. Based on these observations, a hypothesis was developed that ocean water gained access to the molten interior through fissures, and caused volcanic explosions.

If the various phases of this theory are examined more closely, its untenability, both from chemical and physical standpoints, clearly appears. While normal volcanic exhalations doubtless have the same chemical composition as the chief constituents of sea water, this is not a proof that vaporized sea water is actually given off by volcanoes and lavas. It is much more probable that the sea water owes its composition to dissolved constituents of volcanic emanations of former geologic periods and to the products leached from the rocks. This equally well explains the similarity between the compositions of the two.

Furthermore, if the water penetrated to the molten interior through fissures 30 to 40 km. deep, it must have rushed down with enormous rapidity to escape complete volatilization by the country-rock whose temperature must have been much above the critical temperature of water. It is far more probable that the segments of the earth's crust, resting upon a fluid magma, would squeeze the latter upward through the fissures and, forcing the water backward, lead to submarine volcanoes.

But should the water, in spite of all this, reach the molten interior by some means yet unexplained, there would be produced, at the point of contact with the magma, the so-called Leidenfrost phenomenon, and a vapor-film would support the column of water above. Below the point where the water was in the spheroidal state, a cooled

crust would develop, so that the generated water-vapor would not be able to saturate the melt and no eruption would be produced. The vapor itself would probably rise through the water-column, heat it, and eventually cause boiling in the sea. A sudden inrush of water, as here assumed, could only take place in open fissures, but that such exist seems hardly probable in spite of the fact that modern volcanoes actually do occur along great fracture lines. It seems more likely, from the law of hydrostatic pressure, that all fissures extending to the molten magma would be filled by it.

Great inland volcanic eruptions, such as that on Martinique, which have very much the appearance of explosions, are entirely incomprehensible on such assumptions. It is hardly conceivable, with a presupposed fracture reaching the surface, that the magma should break for itself a different path through the rock to spread desolation inland. And how would it be possible for all of the erupted material to be uniformly saturated with moisture if the source was a local contact of the melt with water in the fissure? A solid crust, more than likely, would have formed between the two. Besides failing to account for these great explosions, this theory also fails to give even a fairly plausible reason for the long-continued activity, sometimes increasing and sometimes decreasing, of other volcanoes. In short, a careful consideration of existing conditions shows that the sea water, as such, cannot be the cause for volcanic activity.

The undeniable fact that volcanoes occur along great fracture lines, even though the actual vent may be more or less removed from the fissure, has led to a purely tectonic explanation of volcanic activity; namely, the extrusion of volcanic matter is ascribed to the sinking of the solid crust in other places. If, somewhere, the load resting upon a magma is considerably increased, fissures will develop, and into these the fluid magma will rise, according to the law of hydrostatic pressure, by the sinking of another part of the specifically heavier crust.

It is true that igneous rocks occur primarily where the earth's crust has been broken by great fractures, and especially in regions where the crust was under tension, thus producing favorable conditions for the rise of the magma in the fissure; yet the explosive force of many eruptions can hardly be accounted for on this purely mechanical theory. The phenomena of vulcanism, therefore, will be considered in greater detail.

Petrographic Observations on Vulcanism.—The petrographic study of igneous rocks clearly shows that vulcanism cannot be due entirely to tectonic movements, and that the molten magma itself must possess certain peculiar properties which aid in the eruption. While as yet no explanation of vulcanism can be given which agrees with all physical laws, the accumulation of data is a step toward the solution of the problem.

Two sharply defined groups may be recognized among igneous rocks, especially among those rich in silica and the alkalies. In

one the constituents are more or less uniform in size. Such rocks are called *granular*. They occur in unusually large masses, and solidified between preëxisting strata deep within the earth's crust. They are, therefore, also spoken of as *deep-seated*, *plutonic*, *abyssal* (Gr. ἄβυσσος, bottomless), or *intrusive* (Lat. *in*, in, *trudo*, thrust) rocks. The other group is distinguished by large crystals or *phenocrysts* (Gr. φαίνω, show, κρύσταλλος, crystal), contrasting with a fine-grained groundmass. These are the *porphyritic* (Gr. πορφύρεος, purple, in the translated sense variegated) rocks. Geologically it has been found that the latter rocks are mainly lava streams which were poured out upon the earth's surface. In consequence, they are also called *surface*, *extrusive*, or *effusive* rocks.

The rocks of the first group show a holocrystalline development under all conditions. The second, when fresh, in many cases contain an amorphous remnant or "*basis*" which did not crystallize but solidified as glass, and in this condition filled the interstices between the previously crystallized constituents.

The phenocrysts and the groundmasses of porphyritic rocks represent two stages in the solidification of the magma, and are generally sharply separated from each other. The two generations of minerals show characteristic differences in many cases. For example, the hydroxyl-bearing members of the hornblende and mica groups predominate among the colored constituents of the first generation, while hydroxyl-free augite occurs in its place in the second. These occurrences point to a physical difference in the conditions of formation during the two epochs, a difference brought out more clearly by the fact that in many cases the mica and hornblende of the first generation are partially or entirely *resorbed* (Lat. *re*, again, *sorbere*, to suck in) during the further consolidation of the rock; that is, under later conditions they were unstable.

Resorption is generally more complete the more perfectly the rock is crystallized, so that entirely unaltered biotite crystals with sharp borders are not rare in rapidly solidified, glassy obsidians, while in rhyolite, which is crystalline, they occur only as imperfect remnants. Frequently, too, great quantities of mica flakes or hornblende crystals, some of considerable size, are found in the ashes and sand which make up a great part of the material of the volcanic tuffs, while in the lavas extruded from the same vent, these minerals are almost entirely wanting. From these relationships the conclusion must be drawn that the mica and hornblende crystals had formed in the molten mass before it was erupted. Such phenocrysts, formed when the molten magmas still lay in the depths of the earth, are called *intratelluric* (Lat. *intra*, within, *tellus*, the earth).

The water content of these minerals indicates the presence of water in the melt long before its extrusion, and the instability of the minerals at a later stage is explained, aside from other factors, primarily by the escape of water during the eruption.

Although denied by many observers even in very recent times, numerous observations definitely prove that the melt within the earth is thoroughly saturated with water-vapor and other gases. These were not derived during the eruption from the *vadose* (Lat. *vadosus*, shallow) waters, that is, from the waters circulating near the surface, but, with the other constituents of the compound melt which we call the *magma* (Gr. μαγμα, dough), were condensed and dissolved in the melt during the first stages of the formation of the earth. They are therefore called *juvenile* (Lat. *juvenis*, young). This view is supported by the character of deep-seated rocks, which doubtless were never in contact with surface water. Besides containing fluid inclusions in the individual constituents, they have, to a great extent, a mineral composition which indicates the presence of water during their crystallization.

The chief constituents of silica-rich igneous rocks, such as the orthoclase, quartz and biotite of granite, have never been crystallized artificially by simply melting them together. In the attempted change from the amorphous to the crystalline state, the viscosity is so great that there is a great tendency to undercooling, and the melt solidifies principally as glass. Water-vapor in the magma, however, reduces the viscosity, and these minerals have been produced artificially by melting the proper components under high pressure in the presence of water and other solvents. Since these gaseous substances promote crystallization and mineral formation at the temperatures here obtaining, they have been called *mineralizers* (Fr. *agents minéralisateurs*).

The chemical composition of pitchstone proves the presence of water in the volcanic magma. This rock solidified rapidly under high pressure, and has a water content of 10 per cent. or more, which can only be primary. The great significance of the water content is shown more plainly when recalculated to volume proportions, whereby this amount is found to equal 25 per cent. of the volume of the rock under normal temperature. In a cubic meter of a silica-rich magma, therefore, the water present would amount to 250 liters after cooling. The exhalations from volcanoes show that gases of which no traces remain in the crystallized rock were present in the magma.

Another petrographic observation of importance here is the unmistakable relationship frequently shown by the rocks of one district, one petrographic province,[1] which distinguishes them from the rocks of another.

These relationships have led to the conclusion that our present volcanic eruptions have no direct connections with a molten interior, for the superficial portion of the central melt, which is the only part that need be considered in regard to igneous activity, must be considered a more or less homogeneous mass. On the theory of no connection between the peripheral magma basins and the interior, the petrographic differences between successive eruptions in a single region, or between those in different regions, are more easily explained than on any other assumption.

Stübel's Theory.—It may justly be assumed that the first crust of the earth was weak and full of fissures. The molten material was forced through these cracks and, spreading out, formed a cover above the original crust, as shown in Fig. 1, Pl. I. With continued cooling the crust thickened inwardly and became more resistant to the eruptive forces. The number of outbursts decreased but the intensity of the individual eruptions increased, owing to the greater explosive force necessary to rupture the crust. Enormous masses of solidified material eventually covered the first crust, and became the foundation of Stübel's *Panzerdecke* (armor covering). The magma of succeeding eruptions penetrated this cover and formed within it great chambers filled with molten magma, in part fused from previously solidified material, in part added from below. These are the so-called peripheral magma basins (Ger. *vulkanische Herde*).

As time passed, the Panzerdecke increased in thickness, not only by volcanic activity, but by the gradual cooling of the earth itself. The eruptions gradually became less numerous but in-

[1] The term *petrographical province* was introduced by Judd (*Quart. Jour. Geol. Soc.*, London, 1886, 54) to indicate the fact that rocks erupted in one region present certain well-marked peculiarities in mineralogic composition and microscopic structure, serving to distinguish them from rocks belonging to the same general group which were simultaneously erupted in other regions. Previous to this, however, Vogelsang (1872) had spoken of the similarity of rocks and the possibility of grouping them according to "geographischen Bezirken." Washington (*Carnegie Publication* No. 57, 1906, p. v) suggested the term *comagmatic region*, as not being limited to petrographic characters of the rock. It is used to express the idea that magmas of a certain area have characteristics in common, whether these common characters are due to processes of magmatic differentiation or to other causes. *J.*

creased in violence to break through the progressively stronger shell, until finally a time arrived when the strength of the crust and the inside pressure were in approximate equilibrium. Thereafter, on the rare occasions when the crust was ruptured, the convulsions were enormous, and great masses of molten material were brought upward and produced extensive flows, or forced themselves into the Panzerdecke itself, where they formed peripheral basins of very great size. Eruptions of later geologic times are very insignificant when compared with these mighty flows, and Stübel aptly named this period the Age of Catastrophies. With continued cooling, most of the former conduits were closed, and a section through the crust and the overlying Panzerdecke at this stage probably appeared as in Fig. 2, Pl. I.

From the beginning of the superficial cooling of the earth until this time, the volcanic activity must have been on the increase, but as more and more of the molten material in the vents from the interior solidified, vulcanism gradually decreased in amount, since the increasing thickness of the crust prevented the opening of fresh channels. The volcanic eruptions now generally proceeded only from the peripheral basins, which had lost all connection with the molten interior. Although there doubtless were short periods of increased activity, on the whole the intensity from the Archean to the present has been diminishing. Fig. 3, Pl. I, shows the stage of the earth at the present time.

Assuming Stübel's theory to be correct, the events so far described took place before the deposition of the oldest of the sediments with which we are familiar, and are prehistoric even in a geologic sense. The oldest recognizable documents of the geologic story clearly indicate that the Cambrian and pre-Cambrian periods, usually assumed to be the time of the earliest sedimentation, are actually but late pages in the story of the development of our earth. Thick formations preceded the oldest known sediments but they have left us no more than traces of their former existence, having been practically destroyed in the Age of Catastrophies.

Stübel's theory offers a very convenient explanation of vulcanism, but while its last stages agree well with the events of historical geology, numerous physical observations are opposed to it. The high temperature gradient, primarily, makes it improbable that there is such an enormous Panzerdecke as assumed by Stübel. While the presence of hypothetical peripheral magma basins at various moderate depths may be the cause for the rapid and very dissimilar temperature gradients in different parts of the earth, yet this increase occurs everywhere, and it would be necessary to assume a uniform distribution of such peripheral basins at different, but not too great, depths. Another objection to the theory is the fact that small magma basins, disconnected from the fluid center for whole geologic periods, must long ago have given up their heat to the surrounding rocks and have solidified, as did the enormous masses of deep-seated granitic rocks which erosion has disclosed in so many places. If larger

THE FORMATION OF THE EARTH'S CRUST ACCORDING TO STÜBEL.

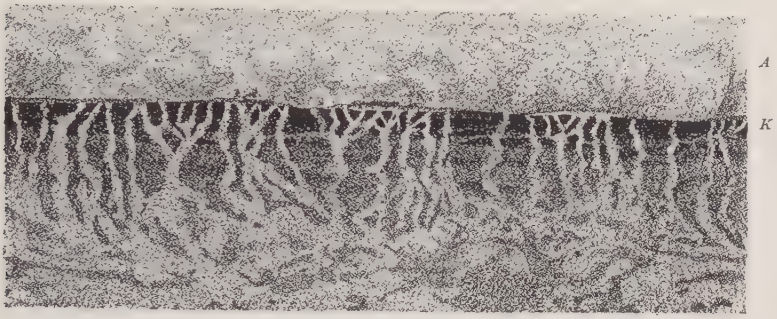

FIG. 1.—Formation of a solid crust *K* which is everywhere ruptured by extrusions of the magma. The atmosphere *A* forms a dense zone of vapor.

FIG. 2. The crust during the Age of Catastrophies. The volcanic activity of past periods has formed a covering (*Panzerdecke*) over the crust *K*. At this stage there are but few conduits connecting the interior with the surface. Through these, however, massive extrusions and intrusions take place.

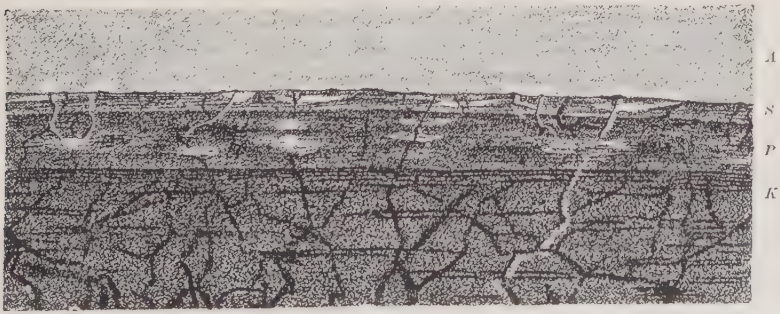

FIG. 3.—The present condition of the crust. All connection between the surface and the interior has been cut off. In the Panzerdecke *P* there still remain molten remnants of former intrusions. These are connected with the surface by channels through the sediments *S*, and produce our small modern volcanoes.

(*Facing page* 20)

molten masses were intruded so long ago in the Panzerdecke, they must have gradually fused their way downward, during the long subsequent periods of time, to form protuberances on the central mass itself, and volcanic activity proceeding from such an attached mass would be the same as from the fluid interior itself. Thus Stübel's theory, while it satisfactorily explains a large number of the geologic and petrographic phenomena of vulcanism, leaves many as unsolved riddles.

The Physical Character of Volcanic Magmas. —Several decades ago the volcanic magma was considered to be in itself inactive, and the whole process of vulcanism was thought to be exclusively the result of tectonic movements. At the present time, at least in many cases, volcanic phenomena are regarded as due primarily to the physical state of the magma itself, for while the majority of volcanoes undoubtedly occur along fracture lines or fissures, such explosive eruptions as those which destroyed Herculaneum, Pompeii, and Martinique, cannot possibly be assigned to tectonic causes. Even though accompanied and followed by earthquakes,

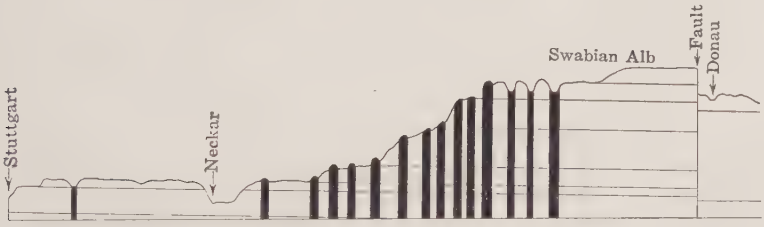

FIG. 4.—Explosion tubes in the Swabian Alb. (After W. v. Branca.)

these were undoubtedly true explosions, which could not have been caused by displacements of the earth's crust. The study of such eruptions clearly shows that the volcanic magma itself must have a tendency to explode. In addition, the folded, faulted, and shattered condition of the country-rock adjacent to large intrusive masses, the formation of contact-breccias, and the injection of igneous material into schists to a distance of over a kilometer, all indicate a considerable activity of the magma itself.

Especially substantiating this view are certain peculiar explosion tubes, called *diatremes*[1] (Gr. δια, through, τρῆγα, hole). These cylindrical or funnel-shaped tubes occur, characteristically, in undisturbed, horizontal strata, and in many cases penetrate them in a sieve-like manner. They are filled with a heterogeneous mixture of volcanic tuffs—brecciated material derived from the country-rock, and rock fragments of all kinds brought up from

[1] Diatremes from the Swabian Alb are well described by BRANCA. (Fig. 4.)

below. They can be explained only by the assumption of mighty explosions which broke through the stratified cover by means of compressed gas, as did that which devastated Martinique several years ago. Such an explosion would tend to blow the volcanic magma out in the form of dust, instead of permitting it to flow as a sheet.

Stübel considered this ability to explode a physical property of the melt, which he assumed would increase in volume at a certain stage of its cooling until it fractured the enclosing shell. But a repetition of expansion and contraction with continually decreasing temperatures, such as must be assumed to occur to account for repeated explosions of one and the same volcano, is unknown in silicate melts. It is true that water reaches its least volume at $+4°$ and again expands below this temperature, but since no known substance has more than one such turning point, it is improbable that such a property is possessed by the silicate melts.

The magma must be regarded as a very complex solution with a high gas content, and it seems probable that the cause of its ability to explode lies primarily in the gases which are set free by the crystallization of the minerals. The cooling of the outer part of the fluid earth, or of Stübel's peripheral magma basins, would cause the superficial layers to solidify, and at the same time would lead to the separation of great quantities of gas, which were dissolved in the magma but which do not enter into the constitution of the crystallized rock.

The significance of these mineralizers follows from the statement made on page 18. The small amount occurring as fluid inclusions in certain minerals of the plutonic rocks represents but a small fraction of the original quantity, for most of them escaped by diffusion into the country-rock and saturated the overlying beds. A part, however, remained in the still fluid magma, since its ability to dissolve gases increased with decreasing temperature.

The amount of gas separated from the melt must be much greater than the amount conducted away, consequently there will be a continual increase in the stresses, and possibly eventually an explosion.

From the petrographic appearance and geologic occurrence of igneous rocks, certain data in regard to the physical behavior of molten magmas may be obtained. For example, aplite, which is a differentiation rock consisting only of quartz and

feldspar, is derived from granite, and differs from it only in its higher content of silica and the alkalies. It must, however, have possessed a much greater degree of fluidity than the granite, for in many cases it extends in fine veinlets to great distances into the rocks surrounding the granite massif. On the other hand, laboratory experiments show that silica-rich melts are very viscous. This difference between the mobility of natural magmas and artificial melts can only be due to the presence of water-vapor and other mineralizers in the former, for silica-rich melts which have lost these gases, in consequence of diminution of pressure by eruption or from other causes, are very viscous.

On account of their greater fluidity, subsilicic magmas are much less dependent upon mineralizers. Silica-poor igneous rocks do not occur in fine veins as aplite does, but much more commonly form broad, blunt-ended dikes. When basic magmas reach the surface, however, they remain relatively fluid, as may be seen by the extraordinary extent of certain lava flows.

Finally, from another difference in the behavior of the two end-members of the igneous rock series, valuable conclusions may be drawn in regard to their genesis. It has been observed that crystalline aplite occurs only within other crystalline rocks, such as granite, rocks crystallized by metamorphism, etc. Nowhere do granular aplites occur in normal, unmetamorphosed sediments, for wherever they cut such rocks they assume the glassy form of pitchstones or dense felsites, the latter formed by the recrystallization of the former. The basic end-members of the igneous-rock series, on the other hand, for example the lamprophyres, are widespread within sediments which not only lie far distant from any volcanic center, but which are entirely unmetamorphosed. Doelter's experiments showed that under normal conditions subsilicic rocks crystallize much more readily than silicic, doubtless on account of their different behaviors at their crystallization temperatures. The points of transition of pyroxenes, olivine, and other basic minerals from the amorphous to the crystalline condition, lie very near their melting points. Quartz and the alkali-rich aluminium silicates, on the other hand, do not crystallize until they reach temperatures considerably below their melting points. Pure melts of these minerals, therefore, solidify before it is possible for their crystallization to begin; that is, at their crystallization temperatures they have become too viscous to crystallize, therefore they remain in an amorphous state. Magmas of this kind can form crystalline aggregates only when their freezing points are lowered to their crystallization points by the presence of foreign agents; they therefore crystallize only where the mineralizers retained in the magma through pressure cause a lowering of the melting points, and where slow cooling favors crystallization.

A small, crystalline aplite dike, therefore, indicates by its very existence that it cooled very slowly and under high pressure. This could only have taken place if the surrounding rocks, at the time of the solidification, were deep within the earth and still hot enough to permit very gradual crystallization.

The Outward Manifestations of Vulcanism.—There are many outward manifestations of vulcanism, but we are concerned here only with the rocks which are produced by it, and can pass over the question as to how far earthquakes are directly related to it.

When insurmountable obstacles lie in the way, a part of the rising magma does not reach the surface of the earth. Such *intrusive* or *deep-seated* rocks solidify within the crust itself. They

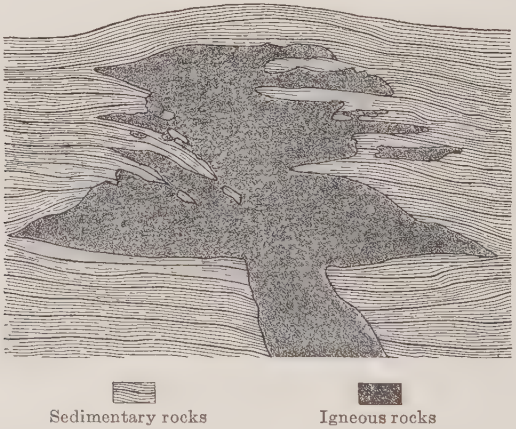

Fig. 5.—Laccolith. The igneous rock has raised and fractured the sediments.

force themselves into places weakened by schistosity, joints, unconformities, etc., and wedge the beds apart. In this manner are formed intruded *sheets* or *laccoliths* (Gr. λάκκος, cistern) (Fig. 5), the latter characterized in many cases by the lifting and fracturing of the overlying beds. Other intrusions break across the strata and form *stocks* (Fig. 6), usually with rounded or elliptical cross-sections. Protected by the overlying beds, these bodies cool slowly and uniformly, and the dissolved gases, becoming insoluble by the crystallization of the silicates, pass off gradually. The rocks, therefore, generally have a uniform, holocrystalline texture, and rarely show different periods of crystallization.

The less massive fissure-fillings generally have a flat form, and are called *dikes*. A system of dikes is shown in plan in Fig. 7,

and the corresponding vertical section in Fig. 8. The textures of dikes vary as much as do their dimensions. They range from pure glass in pitchstones to a holocrystalline development in granitic rocks; from paper-thin veinlets of aplite to enormous dikes hundreds of meters wide.

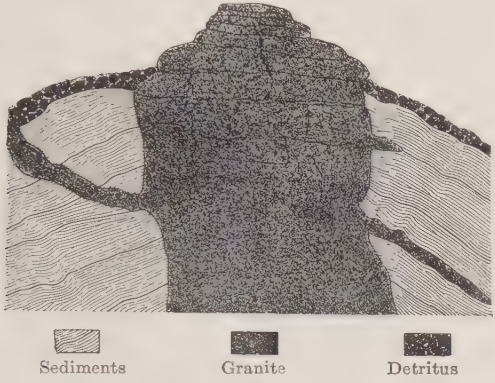

FIG. 6.—Granite stock.

Still other magmas reach the surface of the earth, and form the *effusive* or *extrusive* rocks. Their very variable characteristics depend directly upon their different viscosities and gaseous contents.

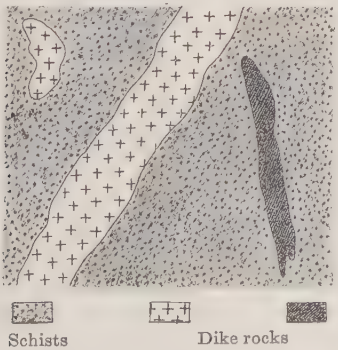

FIG. 7.—Ground plan of dikes.

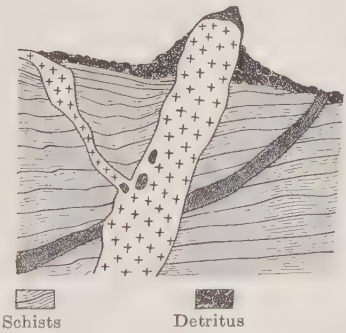

FIG. 8.—Cross-section of dikes.

Ordinarily the magma, rich in gas, ruptures its overlying cover during some great eruption, and enormous masses of finely divided material are hurled forth to become scoriaceous or glassy in the course of their flight. Besides dust-like material, or volcanic *ashes*, there may occur considerable quantities of crystals, previously separated from the melt. Further, there may be coarser lava fragments, the so-called volcanic *sand* and *lapilli*, fragments torn from the country-rock, and masses of plastic material, scoriaceous in character and twisted and contorted in their rapid flight through the air. The latter are known as *volcanic bombs*. All of these, falling around

the mouth of the crater, tend to build up a cone. The magma itself, rising upward, may break through the flanks, or pour itself, stream-like, over the rim. Flowing down the declivity with great rapidity, it will spread itself, when of low viscosity, as an extensive sheet over the surrounding plain. Viscous outpourings, on the other hand, break into fragments during flow, and form the so-called "*block-lava.*" Alternating

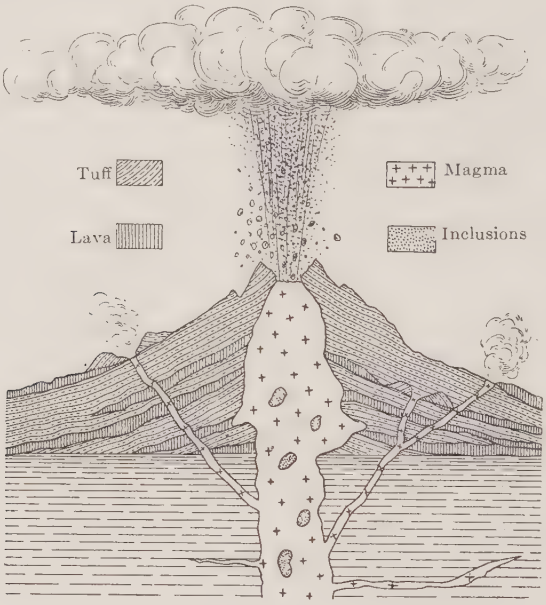

FIG. 9.—Ideal section through a strato-volcano.

eruptions of lava and of this fragmental material or *tuff* form the *strato-volcanoes* (Fig. 9). During very violent explosions fine dust-like material may be hurled to considerable heights and be widely distributed by air currents. This accounts for the constant presence of volcanic dust in recent, deep-sea ooze.

In other cases the rising lava is poor in gases; consequently no great explosions take

FIG. 10.—A lava sheet with channels through which the material was extruded.

FIG. 11.—A lava dome (*Quellkuppe*).

place, and little or no tuff is formed. The molten material wells out upon the surface, where, if very fluid, it spreads out to form extensive *sheets* (Fig. 10) or long *streams*, or, if very viscous, to form cones with steep sides (*Quellkuppen*, Fig. 11). Such volcanoes are made up of a single flow and are called *homogeneous volcanoes.*

Finally, there are volcanoes which sent out no molten lava, or only very small amounts in the later stages of their activity. These are the explosion-tubes or

diatremes mentioned on page 21, and their tuff-filled channels are cut, in many cases, by younger, minor dikes. Such an explosive eruption may break transversely across the strata and blow out the overlying rocks like a cork, or, if the explosive force was insufficient, press upward a rock-complex of rounded cross-section, fracturing the surrounding rocks and reducing them to breccia. In these eruptions neither lava nor tuff may appear, since the rock-cork barred the exit. Such activity has been named *cryptovolcanic*. Fig. 12 is a cross-section through the Steinheimer Basin, where the Klosterberg, a rounded knob of brown Jurassic rocks, was forced upward a distance of about 150 meters through the gritty, horizontal, white Jura.

According to the viscosity and the amount of gas present in a magma, therefore, an eruption will be explosive, and only fine dust-like material will be ejected, or it will be quiet and the material will be entirely molten when it reaches the surface. The strato-volcano is the normal form, but while by far the greater number of recent volcanoes belong to this class, the other forms are not wanting. At Kilauea, Hawaii, the present extrusives are entirely free from tuffs, while in the explosions on Martinique there was no compact effusive rock.

FIG. 12.—Cross-section through the Steinheimer Basin. (After W. v. Branca and E. Fraas.)

The Geologic Age of Igneous Rocks.—Extrusive rocks are being poured out upon the surface of the earth even at the present time. Intrusive rocks, on the other hand, are known only where erosion has removed the overlying deposits. There can be no doubt, however, that plutonic rocks are even now being formed deep within the earth, especially in small peripheral basins; for although volcanic activity was greater in certain geologic epochs than in others, in all of them both intrusive and extrusive rocks can be found.

From the petrographic viewpoint there is nothing more incorrect than the oft repeated assertion that particular igneous rock-types belong to particular geologic formations. Intrusive rocks, doubtless, are found more frequently in the older beds; for example, diabase flows are unusually abundant in the Devonian, massive quartz-porphyry flows in the Dyas, and melaphyres especially characteristic of the Trias in America; but diabases, quartz-porphyries, and melaphyres were also erupted in practically all other geologic epochs; and there are true intrusive masses, undoubtedly quite recent in age, which in all their properties resemble the granites, syenites, etc., of the oldest periods. While

most granites occur in contact with old formations, they are not, *eo ipso*, very ancient rocks, although they are so regarded by many geologists even at the present time. Their almost invariable contact with old rocks is easily explained, for since they solidified deep within the earth, it required long geologic periods for the gradual removal of the overlying sediments. Younger rocks have generally suffered much less erosion, consequently young plutonic rocks are found primarily at high elevations where erosion acted with unusual rapidity. The classic example of such young plutonic rocks is that of the Andes where Tertiary granites were first discovered.

The unfortunate hypothesis that certain igneous rocks occur only in certain geologic epochs led to the widely accepted division of igneous rocks into pre-Tertiary and Tertiary post-Tertiary groups. This classification cannot be upheld under modern petrographic views.

Several decades ago certain investigators attempted to introduce a still more detailed geologic time-classification into petrography. Thus Gümbel called the Silurian diabase of the Fichtelgebirge *proterobase* (Gr. πρότερος, former) to distinguish it from the Devonian, and Paleozoic picrite, *paläopicrite* (Gr. παλαιὸς, old), etc., while certain Hungarian geologists turned the classification topsyturvy by calling a Tertiary granite trachyte!

The classification of igneous rocks according to their geologic age is impracticable, not only from the difficulty of finding characteristic distinguishing marks for the different groups, such as are necessary in a classification, but from the impossibility of determining the ages of innumerable intrusions. It is true that the geologic age of the volcanic activity is easily determinable where sheets and flows occur between sedimentaries, or where they are accompanied by tuffs in which characteristic fossils are found. If the fossil-bearing tuffs are wanting, the accurate determination of the geologic age may be very difficult, since in many cases igneous rocks are intruded parallel to the bedding planes of the sediments. The separation of these more or less extensive injections from lava-flows may be very difficult, especially in the case of basic rocks, unless a scoriaceous texture or injections into the overlying beds indicate the mode of origin.

The difficulty in determining the age of intrusive masses is due to the fact that the overlying rocks may represent the original roof over the intruded material or sediments deposited after the erosion of the original cover. Intrusive masses, it is true, generally metamorphose the enclosing rocks, the metamorphism being restricted to the border zones, or they send dike-like *apophyses* (Gr. ἀπο-φυάς, an offshoot) into them. Furthermore, the border zone of the igneous mass itself may show the effects of contact metamorphism. In beds subsequently deposited, apophyses and border alterations are wanting, but in their place the lowest member may consist of a characteristic basal conglomerate formed by the destruction of the underlying rock, and containing rounded or angular fragments of it.

The characteristics of the two types are different enough to make their separation seem possible in every case by moderately careful observation. Though apophyses be wanting, and the mineralogic alterations within the border zone of the intruded

mass hardly noticeable, yet contact metamorphism in the overlying rocks would definitely prove them to be the original cover. It has become the custom, however, to ascribe a greater metamorphic power to tectonic pressures than to volcanic processes. Thus, in greatly folded regions such as the Alps, all of the alteration is ascribed to the mountain-building forces, which makes it necessary to construct great artificial faults to veil the actual intrusive form of the gneiss-like granites. Elsewhere, however, considerable faulting occurs at the contact of such rocks. This tends to produce friction-breccias whose included rock fragments, rounded by the faulting, so much resemble the pebbles in basal conglomerates that the two rocks may be easily confused.

IV. THE COMPOSITION OF IGNEOUS ROCKS

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Mineralogic Composition.—All igneous rocks are silicate rocks, and their essential original or primary constituents are either silica or silicates. The number of minerals which are of importance in igneous rocks is comparatively small. These minerals are divided into the *essential* or *chief* constituents, which are necessary to that rock-type, and the *unessential* or *accessory* constituents, whose presence or absence does not alter it. Certain of the latter minerals, such as apatite and zircon, are present in very small amounts in almost all rocks, while others rarely occur. In some rocks an accessory may be so abundant that it becomes an essential and characteristic constituent for that variety, for example, titanite in syenite.

In many rocks, especially in those of the nephelite-syenite group, *substitute* minerals (Ger. *Stellvertreter*) occur in the place of some normal, essential component, and thus new varieties of rocks are formed. Furthermore, material from the surrounding rocks

may be dissolved in the melt and later recrystallize in a variety of fortuitous constituents.

The minerals so far mentioned are *primary* constituents which crystallized during the solidification of the rock. Besides these, certain *secondary* constituents were formed later, some of them derived entirely from outside sources through gases or hot solutions, others produced by the alteration of primary minerals. These secondary minerals may be subdivided into those that are crystalline and were produced by post-volcanic processes of replacement, and those that are predominantly colloidal, and probably due to weathering.

The significance of a mineral may be quite different in different rocks. Thus tourmaline, which occurs instead of mica in many aplites, is undoubtedly a fumarolic product in others. Again, epidote may represent a constituent taken from the surrounding rocks, or it may be a secondary product derived from other minerals.

The constituents of igneous rocks may be classified as follows:

I. *Primary Minerals:*

(*A*) *Essential constituents:* Quartz, feldspars, nephelite, micas, pyriboles,[1] and olivine.

(*B*) *Accessory constituents:* Apatite, xenotime, titanite, orthite, monazite, chrysoberyl, perofskite, pyrope, melanite, magnetite, ilmenite, chromite, and pyrrhotite.

(*C*) *Substitute constituents* (Ger. *Stellvertretende Gemengteile*): Tourmaline, eudialyte, cancrinite, catapleite, leucite, melilite, and the minerals of the sodalite group.

(*D*) *Included constituents* (Ger. *Aufgenommene Gemengteile*): Cordierite, almandite, the epidotes, staurolite, corundum, spinel, wollastonite, and some pyriboles.

II. *Secondary Minerals:*

(*A*) *By the addition of material:* Tourmaline, topaz, scapolite, fluorite, hematite, and pyrite.

(*B*) *By replacement:* Mica-like minerals, kaolin, chlorite, serpentine, prehnite, garnets, epidotes, vesuvianite, amphibole, titanite, rutile, anatase, calcite, quartz, and the zeolites.

(*C*) *By weathering:* Primarily, indeterminable amorphous substances. Also calcite and quartz.

[1] A general term covering both pyroxenes and amphiboles. Albert Johannsen: "Petrographic Terms for Field Use." *Jour. Geol.*, XIX (1911), 319.

Certain minerals commonly occur with certain other minerals, or in certain rocks. From this fact a number of *laws of association* for the minerals of the igneous rocks have been formulated, and while a complete review of these cannot be given at the present day, the following appear to be valid:

1. Quartz never occurs as a true constituent in silica-poor rocks that are rich in the alkalies. It is, therefore, not present with nephelite or leucite. Naturally it is more common in silica-rich rocks than in those that are basic.[1]

2. Potash-mica does not occur as a primary constituent in association with pyroxene or hornblende.

3. Olivine is rarely associated with hornblende, orthoclase, or primary quartz.

4. Hornblende is usually accompanied by titanite, olivine by picotite, and melilite by perofskite.

5. Biotite is not abundant in soda-rich rocks, its place being taken by a soda-pyribole.

6. In the plutonic series from granite to gabbro, biotite is most abundant in rocks that are richest in silica and the alkalies. When these are less in amount, hornblende takes the place of biotite, and this, in turn, gives place to augite in the subsilicic rocks. Granites, therefore, are chiefly mica-granites; syenites and diorites, hornblende-bearing rocks; while gabbros usually contain augite.

7. In soda-rich rocks, where hornblende and pyroxene are zonally intergrown, the latter usually forms the outer zone; in calcium-rich rocks the hornblende takes this position.

8. In persilicic plutonic rocks, hornblende is green in more cases than brown; in the subsilicic rocks, when it is a primary mineral, it is usually greenish brown to brown.

9. In the extrusive rocks, hornblende and mica appear primarily as intratelluric minerals. In many cases, therefore, they show magmatic resorption, and the more crystalline the rock, the farther has this proceeded. In the place of these minerals, pyroxene crystallizes during the period of extrusion.

10. Soda-rich pyriboles appear only in rocks that contain more soda than is necessary for the formation of the alkali-aluminium silicates.

11. Melanite and most of the titanium and zirconium silicates (except zircon itself) likewise occur only in soda-rich rocks.

12. Nephelite, leucite, melilite, and the minerals of the sodalite group with the exception of lazulite, are found only in igneous rocks.

Distribution of the Elements.—The percentages of the elements in the accessible portion of the earth's crust may be computed from the chemical composition of the various rocks, assuming that the quantitative distribution of each rock type is known. In such a computation the sedimentary rocks may be neglected, since they were derived from the destruction of igneous rocks, and only the latter need be considered.

The percentages of the elements cannot be computed from a random collection of rock analyses, no matter how complete. Such collections always contain many analyses which are unimportant, so far as determining the average composition of

[1] CLARKE (*Bull.* 330, U.S.G.S., p. 357, and *Bull.* 616, p. 425) suggested the substitution of persilicic and subsilicic for acid and basic when applied to rocks, the latter terms being objectionable on account of their definite meaning in chemistry. *J.*

the earth's crust is concerned, while the number of analyses of important rocks is too small to be representative of their distribution upon the surface. As was shown above, we know nothing in regard to the primeval crust of the earth. It is probable that this possessed the composition of granite, since granite is by far the most common intrusive rock and occurs in the largest masses. It so far predominates that the addition of the proper proportions of other plutonic rocks would produce but a slight change in the chemical composition of the whole. The extrusive rocks, likewise, are of comparatively little importance when compared with the great masses of granite, and besides, the most extensive flows are of quartz-porphyry, consequently also of granitic composition. The average composition of our earth's crust, therefore, is unquestionably much nearer the composition of a normal granite than appears to be the case from any computation yet made, for each of these is based directly upon some collection of analyses.[1] The agreement in the results of the various computations is owing to the fact that the source of error is the same in all.

An example taken from an extensive granitic area will serve as an illustration. Normally the granite is so abundant that its composition will practically correspond to the mean composition of the whole region, and all of the other rocks may be neglected. If, however, the analyses which have been made are examined, it will be found that the very uniform granite is represented by only one, or at most a few, analyses, the majority having been made of very subordinate dikes, among which the lamprophyres are especially abundant. These, however, are poorer in silica, alumina, and potash than the granite, and therefore contain much more of the bivalent metals. All computations based upon collections of analyses show the same error.

The predominant rocks of the earth's crust are orthoclase-bearing; those carrying plagioclase being, by comparison, very subordinate. Potash, therefore, is present in greater amount than soda. This preponderance likewise appears in the composition of the sedimentary rocks, the great majority of argillites, for example, carrying two or three times as much of the former as of the latter.

The composition of the inner core of the earth undoubtedly differs greatly from the mean composition of the crust. This is evident from the density of the earth itself as compared with that of its outer shell. The former being about twice that of the latter, forces us to assume the presence of a metallic core.

Chemical Composition of Igneous Rocks.—Chemical analyses show the percentages of the elements present in rocks, but since most rocks are aggregates of very different minerals, usually of complex composition, it is seldom possible to compute the minerals present in a rock from its analysis. The computation becomes still more difficult if percentages of the different minerals are to be determined quantitatively from the analysis without a previous microscopical quantitative determination of the minerals present. The old method of separately analyzing the portions soluble and insoluble in hydrochloric acid gives results of no practical value; nearly all silicates are attacked by concentrated HCl, the amount dissolved varying greatly according to the length of action, the temperature, and the concentration of the acid.

While valuable and interesting data may be obtained from a

[1] See a forthcoming computation by A. Knopf: *Jour. Geol.*, (1916). *J.*

study of the chemical analyses of igneous rocks, caution is necessary not to over-estimate the importance of a single analysis. There is always danger that one may regard as most reliable those analyses which best satisfy preconceived ideas.

It is very difficult to obtain entirely unobjectionable material for an analysis which is to represent the mean composition of a rock. The small amount of material used makes a total analysis of a coarse-grained or coarsely porphyritic rock too much like that of some specially prominent constituent. Even the analysis of a compact rock is not necessarily representative of the entire mass, for rocks are not stoichiometrically uniform bodies, as are crystals, but usually differ greatly in composition in different places. Thus certain basalts, which appear perfectly homogeneous in fresh condition, under the influence of the atmosphere rapidly develop light-colored patches, due to local aggregations of nephelite. Furthermore, the study of numerous thin sections from a single igneous mass shows the irregular distribution of the individual constituents. A rock-type, therefore, is not to be regarded as being sharply defined chemically, but, much more, as varying between boundaries not too narrow. The strictly chemical tendency of modern petrography has led primarily to a narrow view, for many new rock-types, based on such studies, are only local modifications not entitled to an independent place in a classification.

The chief constituents of igneous rocks are silica, alumina, ferrous and ferric oxides, magnesia, lime, potash, and soda. Besides these, phosphoric acid, titanic acid, zirconium oxide, the rare earths, barium, strontium, and water are usually present in subordinate amounts. Furthermore, in certain rocks, manganese, chromium, nickel, cobalt, tin, uranium, lithium, caesium, rubidium, sulphur, arsenic, antimony, chlorine, fluorine, boron, etc., may occur. For the computation of chemical rock-types, however, it is sufficient to consider the first eight only.

Since all igneous rocks are silicate rocks, they may first be subdivided according to their silica content. This, with very few subordinate exceptions, varies between 78 per cent. and 40 per cent. If SiO_2 is more than 65 per cent. the rocks are called acid, if from 65 to 52 per cent., intermediate or neutral, and if less than 52 per cent., basic. It must be borne in mind that these designations do not correspond to the chemical distinctions between acid, neutral, and basic salts.[1] In a few rare cases, such as in ores differentiated from basic igneous rocks, non-silicate constituents are locally so concentrated that they become essential constituents. These ores are practically silicate-free, but hardly fall under the definition of rocks.

[1] Cf. footnote page 33, *supra*. For this reason the terms persilicic, mediosilicic, and subsilicic are to be preferred. *J.*

Natural melts are not made up of any random combination of elements. There are, for example, silica-rich rocks high in alkali, but no equivalent with high lime and (or) magnesia in its place. Likewise, igneous rocks occur which consist wholly of magnesium silicates with some iron, but corresponding rocks rich in lime and the alkalies are unknown. The proportions of alumina to silica, alkalies, or lime, rarely exceed that necessary to form feldspars. In the few rare cases where such an excess occurs, it probably originated by the assimilation of alumina-rich sedimentary rocks by a normal melt, and does not represent an independent rock-type.

Rocks whose lime content is less than the sum of the alkalies, contain between 78 and 42 per cent. of silica. In lime-rich rocks the silica does not exceed 66 per cent., and in rocks whose magnesia is in excess of lime it is usually below 50 per cent. In sodic rocks the silica decreases with increasing soda, and the soda-orthoclase rocks pass over into nephelite rocks; a high lime content is found only when the rocks are rather basic. On the other hand, in the usual alkali- and silica-rich melts in which potash generally predominates over soda, a decrease in the amount of silica is accompanied by an increase in the lime and at first also of soda, and a decrease in the potash. This brings about a substitution of soda-lime-feldspar for orthoclase, and with a still further decrease in silica, a preponderance of calcic feldspar. With a decrease in silica, therefore, there is an increase in the lime, magnesia, alumina, and iron oxide content, and a decrease in the sum of the alkalies. Lime and the alkalies increase, and alumina and silica decrease in rocks in which lime predominates over the alkalies, that is, the basic minerals which are poor in, or free from, alkalies and alumina become more and more prominent. Alkalies and alumina decrease along with the silica in rocks with more magnesia than lime, and the rocks become feldspar-free. The next step is the disappearance, also, of the lime, and the extreme end-member, the pure orthosilicate rock olivinefels, contains only the silicate of magnesia and iron.

Physico-chemical Laws of the Magma.—The facts just stated make justifiable the conclusion that igneous magmas do not consist of any random combination of substances, but that the different components are present in definite proportions, after the manner of salts in a solution. Like salts in solution, also, they are probably more or less dissociated, but a definite balance, depending upon exterior physical conditions, governs their mutual relationships.

From a physico-chemical standpoint, magmas are natural, mixed solutions of rather complex character. In most cases there were present in the original melt, besides the constituents which can be recognized in the solidified rocks, variable amounts of the so-called mineralizers—gases which acted as solvents and permitted the rock to crystallize more readily. Corresponding to the

relationships in a solution, *the sequence of crystallization of the individual minerals was determined by the degree of their solubility in the remainder of the magma*, and therefore they did not crystallize out in the order of increasing fusibility.

The textures of plutonic rocks show that the magmas were very fluid during their periods of crystallization. In contrast with contact-rocks, which are to be considered later, the individual constituents of the plutonic rocks are generally rather poor in inclusions, and many of them show rather perfect crystallographic outlines, characteristics which would probably not have appeared had the magmas been very viscous during crystallization.

It is of interest to know that the Neptunists did not believe it possible for a melt to crystallize, but thought it solidified in an amorphous form. The solidified masses were supposed to undergo a later crystalline transformation (hysterocrystallization; Gr. ὕστερος, later), either through the agency of circulating water or by a gradual inner molecular change in the solid state, somewhat analogous to a process which takes place in certain metals. The latter process is regarded, at the present time, as the cause of some crystallo-genesis, but in the formation of rocks it is probably of rather subordinate importance.

In considering the processes of crystallization according to the laws of solutions, it must be kept in mind that crystals cannot separate from a melt so long as its temperature is higher than the crystallization temperature of the substance at a given pressure. Below this point, the crystallization of the mineral may begin whenever the point of saturation of the solution, under the given physical conditions, is exceeded. A very considerable lowering of the melting point is often noticed in complicated mixtures. Even in the simpler silicate melts, this reduction may be as great at 400°.

Most rock-forming minerals occupy less volume in the crystallized condition than in the fluid, and their fusibilities and solubilities are less at high than at low pressures. Relaxing the pressure, therefore, in many cases has the same effect upon crystals already separated as increasing the temperature, and a partial or complete re-solution corrodes or resorbs the first products of crystallization, as is characteristically shown by the quartz or olivine phenocrysts of certain extrusive rocks. The amount by which the melting point is increased by pressure is not very great, and increase in pressure does not raise it indefinitely, for there is a critical point above which the substance remains fluid under any amount of pressure.

The phenomenon of resorption, seen in the corrosion of crystals of quartz or olivine, and the resorption and molecular rearrangement of hornblende or biotite, occurs chiefly in the extrusive rocks.

It is the more complete the more crystalline the rock, and the greater the loss of mineralizers during the volcanic eruption.

The first minerals to separate from a granite magma are, in general, the accessory constituents, such as zircon and apatite, which are least fusible. The facts that they separate early and are present in minute quantities, indicate their slight solubility in the remaining magma. In a later stage of the solidification of the rock there appears, with the gradual cooling, a saturation for the ferromagnesian silicates. Thus, when the magma has sufficiently cooled, biotite may crystallize and in its solidification enclose great numbers of previously formed apatites and zircons. The separation of the biotite goes on slowly and uniformly since it becomes more and more insoluble with further decrease in temperature. Gradually, also, the point of saturation for lime-bearing plagioclase is reached, and this now separates with the biotite. The orthoclase follows, the ferromagnesian salts having become by this time completely exhausted. Quartz remains liquid at relatively low temperatures, since it is most easily soluble in the mineralizers, and therefore becomes more and more concentrated in them until it crystallizes as the last mineral. The mother-liquor of the granite, therefore, in every stage of its solidification, is richer in silica than the solidified rock.

In a similar manner the change of the sequence of crystallization in basic rocks, in which the bivalent metal-rich bisilicates are concentrated in the mother-liquor, may be explained.

With the crystallization of some of the material, the composition of the remaining magma alters; thus the glassy base of a persilicic or intermediate rock is richer in silica and the alkalies than the average of the whole rock. This gradual alteration in the chemical composition of the melt in many cases leads to the development of zones in the growing crystals. For example, a plagioclase feldspar may be rather high in lime in the first period of its crystallization, but, as the proportion of lime in the magma decreases, layers progressively richer in soda are added. The sequence generally is as here given, the border zones being richest in soda and silica. Similar differences may be noticed, not infrequently, on comparing the plagioclase phenocrysts of a rock with the same mineral in the groundmass. The latter is always richer in soda.

Numerous valuable data are obtained by applying the theory of solutions to the separation of minerals from a magma. The natural magmas, however, are so complex that the overlapping of the different processes somewhat obscures the significance of each.

The study of eutectic (Gr. εὖ, good, τέκτων, builder) mixtures has produced valuable results. These mixtures consist of two or more substances in a single solution from which the dissolved bodies crystallized simultaneously in intimate intergrowths. A eutectic mixture of two or more given substances has a constant composition, and changes proportions but slightly with a change of pressure. If one of the substances is present in greater amount than required by the eutectic mixture, it crystallizes first and continues to do so until the composition of the eutectic is reached. For example, the eutectic mixture of quartz and feldspar, which

is seen in graphic granite (Fig. 13) and in the micropegmatitic, spherulitic, and glassy groundmasses of quartz-porphyries, consists of about 75 per cent. of feldspar and 25 per cent. of quartz. From quartz-rich magmas, containing a mixed solution of the two, the quartz will crystallize before the feldspar, producing the so-called *granulitic* texture (Pl. II, Fig. 2). If the amount of feldspar exceeds the eutectic mixture, feldspar will separate first, producing the *granitic* texture (Pl. II, Fig. 1). A reversal in the sequence of crystallization of feldspar and the dark constituents is produced in a similar manner.

It was formerly thought that magmas solidified at exceedingly high temperatures, but modern experiments have shown that these

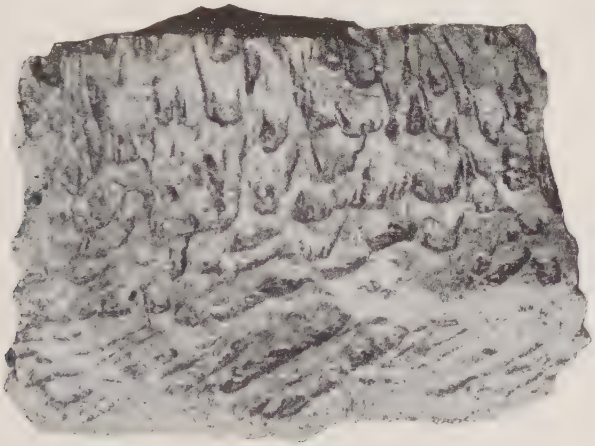

FIG. 13.—Graphite granite from Jekaterinburg, Urals.

are far below those which may be reached in the electric furnace.[1] The solidification temperatures are especially low in the soda-rich rocks, such as those in which aegirite and arfvedsonite occur as the first products of crystallization.

If the temperature at which a magma is saturated with a certain mineral lies above the melting point of that mineral, there will occur, in place of crystallization, a sort of *liquation*, that is, there will appear two melts, insoluble in each other. The partial magmas will solidify later, perhaps simultaneously, perhaps one after the other, and the rock will show *schlieren*. If one of the

[1] Observations made by DAY and SHEPHERD ("Water and Volcanic Activity," *Bull. Geol. Soc. Amer.*, XXIV (1913), 601) show the temperature of the Hawaiian lavas to be between 1,070° and 1,185°C. at the surface. *J.*

partial magmas is much more fluid than the other, it may solidify with sharply defined borders. In such a case the inclusion may

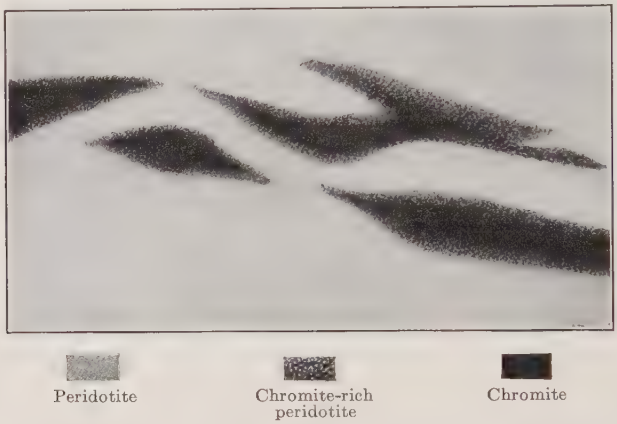

FIG. 14.—Schlieren of chromite in peridotite, showing transition zones.

have the appearance of a later intrusion, for the more mobile partial magma, having penetrated fissures and contraction cracks

FIG. 15.—Dike of nickeliferous pyrrhotite in gabbro, showing reaction rims.

in the portion first solidified, intersects it in dike-like forms and produces the impression of an independent body.

The first relationship is the more widespread. Schlieren-granites, banded gabbros, and chromic iron segregations in peridotites are examples. It may be observed, especially microscopically, that in this case the two parts are generally united by narrow transition zones, the separation not having been complete in the fluid state (Fig. 14). In the case of nickeliferous pyrrhotite segregations in gabbro, the ore may have solidified after the beginning of crystallization in the main rock. It usually occurs in sharply defined, dike-like forms, in many cases broken into disconnected parts, as though by movement of the gabbro during the last stages of its solidification (Fig. 15). Transition zones between the ore and the gabbro are not present, but in many places the latter was metamorphosed at the contact and shows reaction rims.

Action of Mineralizers.—It has been shown synthetically that the crystallization of the different essential constituents of igneous rocks depends, more or less, upon the physical conditions under which the cooling takes place. Attempts, such as those of Michel-Lévy, to produce igneous rocks artificially, have shown that it is easy to crystallize the constituents of subsilicic rocks, primarily olivine, augite, basic plagioclase, nephelite and leucite, by slow cooling from a simple silicate melt. Under similar conditions, however, orthoclase, quartz, biotite, and hornblende cannot be made to crystallize.

Quartz and orthoclase, the chief constituents of the persilicic rocks, do not crystallize from simple melts because their melting points are more than 100° above their crystallizing points. However much the cooling be retarded, the amorphous form, that is glass, is produced. If, however, the melting points are reduced by proper means to the temperatures of crystallization, these minerals also pass directly from the melt into the crystalline condition. In nature this lowering of melting points is produced primarily by the gases and vapors, especially water gas, retained in the magma by high pressure. These gases, acting as solvents, keep the minerals in fluid condition until the temperature is far below that at which they would otherwise solidify, thereby making possible their crystalline development.

These *mineralizers* are of importance from another standpoint, for hydroxyl-bearing minerals, such as mica and hornblende, not uncommonly occur as the first products of crystallization from the melt, especially in the silica-rich rocks. In fact the micas and amphiboles cannot crystallize from water-free melts. On the other hand, the most essential constituents of the subsilicic rocks, such as basic plagioclase, pyroxene, and olivine, are minerals whose crystallization temperatures are very near the solidification point of the melt, consequently rocks which contain them crys-

tallize readily from simple melts, and even though the mineralizers may have escaped from the subsilicic magma during its extrusion, the rocks do not necessarily develop a glassy habit but may even be holocrystalline.

A comparison of plutonic rocks with surface flows clearly shows the significance of the mineralizers. In the former, they remained in the magma on account of the pressure of the overlying strata, in the latter they escaped as clouds of vapor when the pressure was removed from the melt. The change in the physical conditions under which the crystallization took place is very distinctly shown in the appearance of the rocks, and, as might be expected from what has been said above, this is most marked in the silicic rocks.

Granitic rocks must have solidified at a considerable distance beneath the surface of the earth, and the crystalline development of the biotite, orthoclase, and quartz, indicates that mineralizers were present, while the uniformity of the texture shows that the solidification took place under conditions of uniform cooling.

If an upward movement of the magma relieved the stress and permitted partial escape of the enclosed gases and vapors, this fact is expressed in the texture of the rock, which then appears porphyritic, and the larger *intratelluric* (Lat. *intra*, within, *tellus*, earth) phenocrysts of feldspar and quartz, which were formed under the uniform conditions of the interior of the earth, stand out from the more or less dense groundmass, whose texture expresses the later conditions of formation. Finally, if the melt reached the surface as a lava-stream, all of the mineralizers were completely lost. If the magma was that of a normal granite, the constituents could not pass from the fluid phase into the crystalline, but that portion which did not crystallize in the deeper zone, solidified as glass. In many cases the change in the condition of the melt caused it to react upon the previously crystallized minerals, which, though stable under the conditions of formation, now became unstable, and were either entirely dissolved, or corroded and embayed. Thus the hydroxyl-bearing micas and hornblendes may have been entirely destroyed or magmatically resorbed, and augite may have taken their place. As a result, the deep-seated granite differs essentially in texture and mineral composition from the chemically equivalent, extrusive rhyolite (liparite).

On the other hand, there is no such marked difference between gabbro and basalt, which are silica-poor, and normally consist of labradorite, augite, and some olivine. Even the extrusive members of this group show a pure crystalline-granular development without an indication of porphyritic texture, and under certain conditions may be quite coarsely crystalline, for example, in massive flows which permit slow cooling.

But even the less massive sheets of these subsilicic rocks appear holocrystalline under the microscope, glassy rocks being practically wanting. This holocrystalline development of relatively thin sheets of trap, seen at the Wener Sea in Sweden, in the Hebrides, and in Iceland, stands in marked contrast with the common occurrence of holohyaline rhyolite, such as that in the Glashüttental near Schemnitz in Hungary, or in the Yellowstone Park.

The mineralizing agents ordinarily do not enter into the composition of the solidified igneous rocks, but pass off, either quickly in the form of great clouds of vapor during a volcanic eruption, or slowly and uniformly deep within the earth, as they are excluded by the crystallizing minerals, to diffuse through the highly heated

country-rock and renew their mineralizing activity. By this means they become of great importance in the alteration of the country-rock, and are therefore classed as agents of contact-metamorphism.

Finally, mineralizers play an important part in the formation of the so-called complementary dikes—subsequent extrusions of differentiated rocks—especially when these are rich in silica and the alkalies. The differentiation rocks, therefore, may be very coarse-grained like the pegmatites, or the texture may be more or less porous with cavities filled with well-developed crystals, indicative of their growth in the presence of concentrated mineralizers.

It is noteworthy that different natural magmas contain very different amounts of mineralizers. As just mentioned, those that are rich in silica and the alkalies contain great amounts, while subsilicic rocks, rich in the alkaline earths, contain but little. This is shown by the intensity of the contact-metamorphism, by the development of pegmatite, and by other evidence. The country-rocks of granites, and more especially of the alkali-rich nephelite-syenites, may be altered to a distance of many kilometers, and they are usually cut by numerous pegmatites filled with interesting minerals. On the other hand, in the much rarer intrusive rocks which are poor in silica and rich in the bivalent elements, both contact-metamorphism and pegmatites are much less common.

The relation between mineralizers and the character of the rocks is further shown by the fact that subsilicic igneous rocks, recognizable by their mineral composition and preserved remnants of textures as having been originally gabbros, traps, or even labradorite-porphyrites, are completely recrystallized at the contact with granites or nephelite-syenites. Without having undergone any essential change in their chemical character, they are altered to rocks composed of entirely different minerals. Thus gabbros or porphyrites, which originally crystallized from magmas poor in mineralizers, were altered to amphibolites and eclogites by the action of mineralizers emanating from alkalic rocks. If the original magma had been rich in mineralizers, rocks similar in mineral composition to eclogites and amphibolites undoubtedly would have resulted directly from the first consolidation.

The effect of mineralizers on the composition of a rock is undoubtedly seen in these contact-rocks. In some cases, however, the mineralizers did not act alone but were aided to some extent by the great pressures which acted upon the magma during the orogenic movements, as is well shown by the phenomenon of piezocrystallization which is described in a later chapter. Of especial interest, in this connection, are certain peculiar jadeites which occur in serpentine. Chemically they consist of one part nephelite and one part albite, but their specific gravity is much higher than an aggregate of these two minerals [Jadeite (sp. gr. 3.3) $2NaAlSi_2O_6$ = nephelite (sp. gr. 2.6) $NaAlSiO_4$ + albite (sp. gr. 2.6) $NaAlSi_3O_8$].

The amount of tuff occurring in association with extrusive rocks depends to a certain extent upon the amount of mineralizers present in the magma; the more gas, the more dust-like material hurled forth by its escape. In fact, an excessive amount of gas may lead to a great explosion, and cause the shearing of a smooth

passage through the earth's crust and the ejection of much finely divided material, which falls back and is deposited in and around the mouth of the crater. The tuff produced by such explosive eruptions is either of the character of the most silicic of the igneous series or, strangely enough, of the most basic of the differentiation rocks. The rhyolite-tuff at Ries near Nördlingen, Bavaria, the enormous masses of quartz-porphyry-tuff at Bozen in South Tyrol, and the pumiceous tuff with the composition of a soda-rich trachyte—the so-called trass—in the Brohl valley near Andernach, are examples of the first class, while the melilite-basalt-tuffs of the Swabian Alb and the diamondiferous kimberlite of South Africa are examples of the second.

The subsilicic igneous rocks, with the exception of these basic differentiation rocks, were very poor in mineralizers. This is shown, for example, by the lava at Kilauea, which gives off no vapors,[1] and by numerous basaltic "Quellkuppen" (Fig. 11) which are practically unaccompanied by tuff.

Magmatic Differentiation.—In many cases the texture and composition of an igneous body is not uniform throughout, but within it there are parts which differ decidedly in composition from the main mass, yet are united to it by all possible transitions. Such irregular masses are spoken of as *schlieren*. They may be subdivided into (*a*) *Constitution-schlieren*, originating in the complete splitting up of a previously uniform magma; (*b*) *Differentiation-schlieren*, produced by a gathering together of the material first crystallized; (*c*) *Resorption-schlieren*, originating in the partial assimilation of included fragments of the country-rock (the dark basic patches (*Putzen*) occurring in many granites probably belong here); (*d*) *Injection-schlieren* or schlieren-dikes, which were formed during the last stages of the solidification of the rock by the injection of molten material into shrinkage fissures. Finally (*e*) the last remnant of the melt itself, which in general is characterized by an enrichment in mineralizers, may separate into schlieren-like masses of pegmatite. These are called *hysterogenic schlieren* (Gr. ὕστερος, later, γιγνομαι, to be born).

Magmatic differentiation in igneous rocks may be on a large or on a small scale. Numerous great granitic masses consist of unlike rocks, and in many cases, especially in stocks, the silica and

[1] For the contrary see Day and Shepherd, *Op. cit.* J.

alkali content gradually decrease from the center to the border, so that there are all transitions from a silicic, orthoclase-quartz rock at the center to a subsilicic aggregate of plagioclase and pyroxene at the border (Fig. 16). In spite of the great chemical and petrographical differences between the gabbro-like borders and the granite interior, all the transitions are considered *facies* of the granite, being parts of the same geologic unit.

Furthermore, the various lava flows of a petrographic province show chemical and petrographical differences, indicating a very gradual change of the magma from subsilicic to silicic. This is one of the chief arguments in favor of Stübel's theory, suggesting

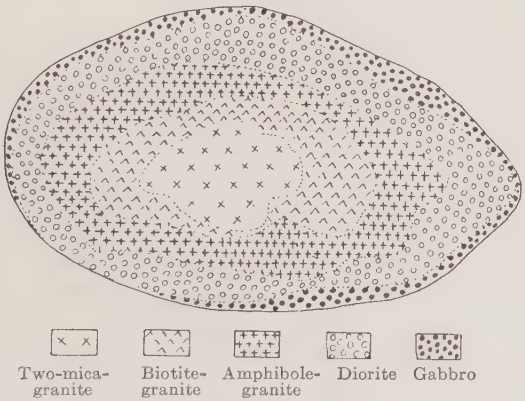

FIG. 16.—Magmatic differentiation in a granite stock.

that magmatic differentiation took place in one of the hypothetical peripheral magma basins in a manner analogous to that in the granite stock, most of the insoluble constituents, in this case the lime-iron silicates, being concentrated against the cooler roof, while silica and the alkalies increased with depth. The first lava extruded having come from the upper portion of the basin and succeeding flows from deeper and deeper levels, the composition of the erupted rocks becomes progressively more silicic.

The silica-poor melt, which segregated in the higher levels, was undoubtedly specifically heavier than the silica-rich magma of the deeper zones, yet a study of the igneous rocks shows that specific gravity plays no important rôle in the arrangement of the constituents even in the case of the heavier ores, great masses of ilmenite, magnetite, chromite, and presumably also of platinum, occurring in schlieren-like segregations and not at the base of the igneous body with which they are associated.

In many cases of this kind the nature of the igneous rocks, as well as of their schlieren, excludes the assumption that the magma was so viscous, at the time of the formation of the schlieren, that separation could not take place by specific gravity.

Other physical influences, therefore, perhaps electric or magnetic, must have counteracted the effects of specific gravity.

This phenomenon deserves especial attention because differentiation by specific gravity has undoubtedly taken place at the earth's center, the inner core being much denser than any known igneous rock. The specific gravity of the whole earth (5.2) is twice that of the known crust; its inner parts, therefore, must contain much heavier substances than those which compose its shell. It was formerly supposed that the molecular weight of the individual constituents was the cause for this difference. The earth's crust was thought to be built up of zones, the outer one, of lithium-bearing granite, passing into rocks containing soda and potash. Deeper down, strata of basic magmas graded into pure magnesia-iron silicate melts and finally into the supposed metallic core. These assumptions had no field observations to support them, and were purely theoretical.

Differentiation on a small scale is seen where inclusions occur in silica-rich igneous rocks. Through the partial solution of the constituents of these inclusions the equilibrium of the magma is

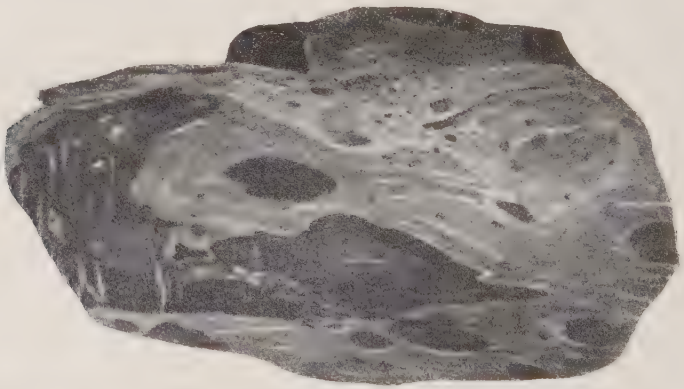

FIG. 17.—Gabbro-diorite border facies of granite with schlieren due to inclusions. (From Webern, Neunkirchner Höhe, Odenwald.)

disturbed and differentiation takes place, in many cases causing distinct banding (Fig. 17). The same phenomenon occurs on a more extensive scale where the inclusions are large. In such cases, in the otherwise haphazard (*richtungslos*) granular granite, these fragments are surrounded by zones of gneiss showing parallel structures due to magmatic differentiation.

A banded development, much like bedding, is found in many subsilicic igneous rocks, especially in gabbros (Fig. 18), and banded areas also occur in nephelite-syenites and peridotites.

Many intrusive rocks show the effects of magmatic differentiation in their narrow border zones, the variation being especially great where silica-rich rocks, like granites, have broken through

rocks rich in lime. In such cases the whole series of plutonic rocks may appear within a relatively short distance, the granite of the central mass grading into pyroxenite and peridotite at the contact.

Local differentiation processes of this kind had a limited period of action, for they ceased upon the crystallization of the magma. The transition diorites or gabbros, therefore, were usually formed under abnormal conditions, and as a consequence differ from normal types in many particulars. The magma nearest the contact dissolved considerable lime. The melt, therefore, was lime-rich and silica-poor and, at the same time, carried a little magnesia and iron, and much alkali. Such a chemical combination does not occur in igneous rocks; it therefore represents an unstable condition of the magma. Diffusion must immediately have set in and have produced an increase in magnesia and iron at the periphery of the mass and a decrease in the alkalies,

FIG. 18.—Banded gabbro. Isle of Skye. (After A. Geikie.)

the latter enriching the granite itself. Thus the tendency of the magma toward equilibrium, represented by the normal igneous-rock series, again appears.

These *endogenic* contact phenomena are generally much less distinct at the contact of granitic rocks with slates, for the difference between the composition of the dissolving and the dissolved material is not so great. Yet even here, in many cases, a close examination will show that the adjacent rock has been dissolved, and garnet, cordierite, and aluminium silicates or corundum and spinel will be found in the intrusive. The assimilation zone at the contact with the slate, also, is much less silicic than the granite itself, that is, it is richer in mica and poorer in orthoclase, the latter usually occurring only as large, sporadic phenocrysts.

Basic border zones of this kind are common, and most of them are undoubtedly due to an assimilation of the adjacent rock. In some places they are very poor in quartz but rather rich in orthoclase (mica-syenite in part), elsewhere the feldspar is almost wholly plagioclase (mica-diorite in part). In both cases, however,

the rocks are more *melanocratic* (Gr. μέλας, black, κρατεῖν, to dominate) than the corresponding normal rock and, except for their granular texture, very closely resemble lamprophyres.

The significance of border zones in which silica and the alkali-rich minerals predominate is entirely different. Such rocks are light-colored or *leucocratic* (Gr. λευκός, white) and correspond in composition to the aplites. They are found, for example, around the granites of the central Alps, and are especially typical of the tin-granite of the Erzgebirge, where they usually show a coarse-grained, pegmatite-like development.

The leucocratic border rocks show that the mineralizers were exceptionally concentrated in the aplitic magma, making it extremely mobile and causing it to penetrate the shattered contact-rocks with great ease, in many cases saturating them completely. The intruded rocks in injection-schists[1] are generally aplite or pegmatite veins.

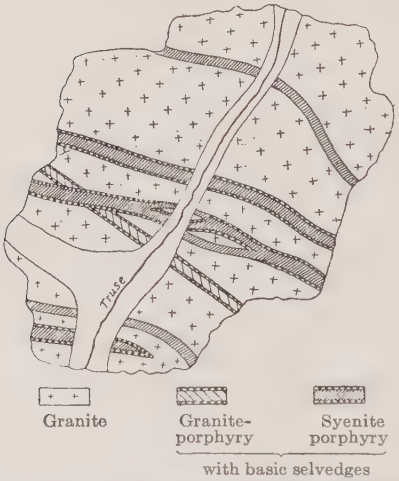

FIG. 19.—Differentiated dikes in the Trusetal, Thüringen. (After H. Bücking.)

Differentiation rocks are found not only around large masses of plutonic rocks, but also very commonly as selvedges of relatively subordinate dikes. The lamprophyric and aplitic borders of the dikes (Fig. 19) so commonly intersecting granite, however, cannot be explained on the basis of assimilation of the adjacent rock. Here the magma suffered internal differentiation, In the case of the aplite, the borders not rarely are more completely crystalline than the dike itself, for example in the quartz-porphyry dikes near Regensburg where the selvedges are of normal granular aplite. But an *increase* in the crystallinity of the border zones is found only where dikes were intruded immediately after the intrusion of the main mass itself and while it was still extremely hot. Later dikes and those extending farther from the parent magma are rich in glass and fine-grained at the borders.

Complementary Dikes.—The differentiation processes so far mentioned, which all took place where the intruded mass itself solidified, are called *laccolithic differentiations*. Contrasted with these are the *abyssal* differentiation processes which took place deep within the earth, and which produced, within peripheral magma basins, all normal magmas and the various rocks of a single

[1] The term injected-schist is frequently used. Injection-schist is better, the granite being the injected rock. *J.*

petrographic province. Here also belong the differentiation processes which produced the *complementary* or *satellite* (Ger. *Ganggefolgschaft*, literally dike-retinue) rocks which in so many cases followed the plutonic rocks, and usually, though not always, cut them in the form of dikes. The term *Ganggesteine* (dike rocks), originally used by Rosenbusch, is not an accurate term for all occurrences, and it is perhaps better to substitute *differentiation rocks*, since they always show certain chemical variations from the normal magma.

A great variety of differentiation rocks is associated with nephelite-syenite, its magma being especially subject to splitting. Most of these differentiation products, however, properly should not be called rocks, for they are much too unimportant and only of local significance. Naming each mineral combination produces great confusion in the nomenclature and causes a loss of perspective by magnifying the importance of these isolated occurrences, making the relationships appear much more confusing than they actually are. The relation of the differentiation products to the parent rocks is much more easily understood in the granite series than in the nephelite-syenite, consequently they may be used as types of the complementary dikes.

Rocks of the composition of the main igneous mass are rare among the succeeding dike-intrusions. From their undifferentiated condition they are called *aschistic* (Gr. *ασχιστὸς*, unsplit) rocks. The dikes cutting the parent rock are usually somewhat lighter or somewhat darker than the latter, and represent limiting cases of differentiation. Such dikes are called *diaschistic* (Gr. *διασχιστὸς*, cleaved). When light in color they belong to the aplitic differentiation series, when dark to the lamprophyric.

The intimate relationship between the differentiation rocks of the granite family are shown in Fig. 20. Aplite (Gr. *ἁπλόος*, simple, therefore more properly called haplite) occurs when there is an increase in silica and the alkalies, and a decrease or complete lack of dark constituents. Lamprophyres (Gr. *λαμπρός*, brilliant, on account of the appearance of the mica-rich varieties) occur when an increase in the bivalent bases produces an increase in the amount of the dark constituents. With these changes the proportions of the alkalies are altered, orthoclase rocks, with predominating potash, resulting on the one hand, and potash-poor plagioclase rocks on the other. The orthoclase series begins with ordinary, fine equigranular, orthoclase-rich, biotite-free aplite, and leads through the transition member semi-aplite, which contains a little biotite, to granite-porphyry. From aplite to granite-porphyry the rocks approach nearer and nearer the composition of normal granite. Under certain conditions they may develop a lamprophyric facies by becoming richer in the ferromagnesian constituents. In this case they become darker, and from brownish-black minette without feldspar phenocrysts, there is a rapid transition to proterobase with practically no orthoclase, and therefore rather representing a subsilicic, plagioclase-rich, granitic lamprophyre.

With still more plagioclase, the aplites become true plagioclase rocks; thus many megascopically normal aplites are rich in albite. Further, the semi-aplitic alsbachite

contains a lime-soda-plagioclase as its chief feldspar, and the lamprophyres of this series are generally still more calcic. On the other hand, proterobase, which normally carries a calcic feldspar, not infrequently contains albite as the only plagioclase, but this is usually secondary, being derived from the calcic plagioclase by metamorphism.

Finally, both end-members of these differentiation rocks are feldspar-free. At one extreme the aplites become aggregates of pure quartz, numerous quartz dikes being true differentiation rocks, while at the other the proterobase loses its feldspars, and the resulting picrite-porphyrite, which consists chiefly of olivine and pyroxene, represents the most basic of the granitic differentiation rocks.

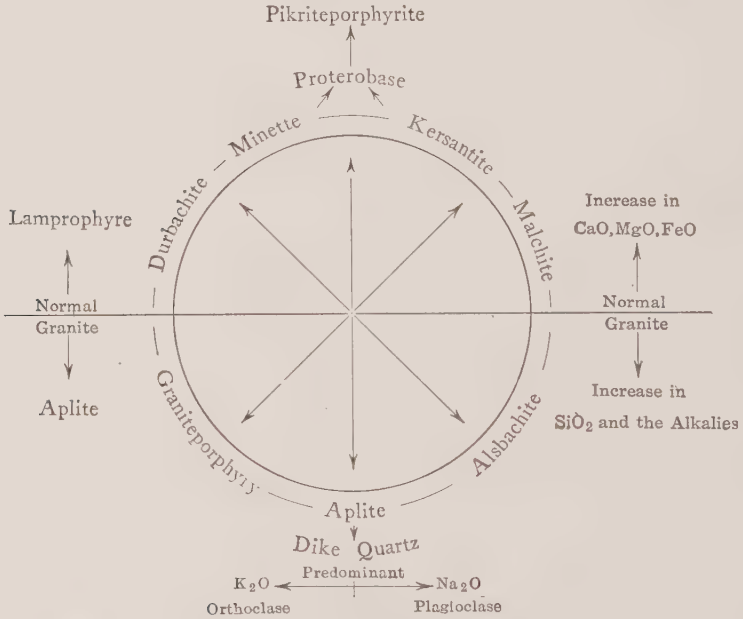

FIG. 20.—Diagram showing the relationships between the granitic differentiation rocks. (After B. Sandkühler.)

The silicic differentiation rocks, especially aplite, were derived from melts rich in mineralizers, and in many cases contain much tourmaline; normal tourmaline-granite, like muscovite-granite, being a form of aplite. All mineralizer-rich magmas are very sensitive to changes in physical conditions during their consolidation, consequently when an aplitic magma was extruded at some distance from the volcanic center, or when its period of intrusion came long after that of the main mass, the rock developed into aplite-porphyry, resembling quartz-porphyry, or pitchstone-porphyry rich in glass. The largest known occurrences of pitchstone were derived from aplitic magmas which solidified as glass and they carry the greater part of the mineralizers in solid solution. From

chemical analyses of such natural glasses some idea of the enormous amount of gas which was contained in the magma may be obtained. Thus fresh pitchstone from the neighborhood of Meissen contains as much as 10 per cent. by weight of water.

The behavior of the lamprophyres is entirely different. Their magmas originally were probably less rich in mineralizers, consequently much less fluid, than the aplitic magma. The aplites, therefore, in many cases branch into fine veinlets (Fig. 21), while lamprophyres form stock-like masses or very simple dikes with broad and blunt ends (Fig. 22). Aplite is crystalline only within

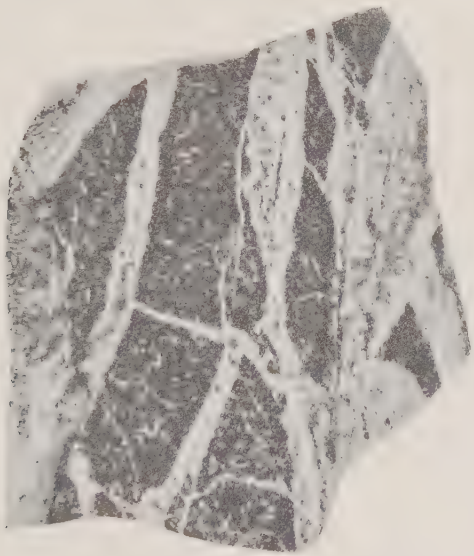

FIG. 21.—Aplite dike in amphibolite. Untersulzbachtal, near the Grossvenediger.

the zone of contact-metamorphism; the lamprophyres in many cases show no alteration in their character even when rather far distant from the igneous center, or when within entirely unaltered sediments, and they show a glassy development only under exceptional conditions.

In the porphyritic lamprophyres the only true phenocrysts are mica, hornblende, and (or) pyroxene, yet here and there exceptionally large, phenocryst-like individuals of orthoclase and quartz are found. If these larger crystals are examined carefully, it will be seen that they differ from true phenocrysts in being more or less rounded, as though fused at the edges (Fig. 23), an indication

that they were formed deep within the earth in the granitic magma itself, and were removed from it by the lamprophyres during their extrusion. Such *primeval inclusions* are extremely numerous in some lamprophyres and in true basalts, olivine inclusions in particular being rarely wanting in the latter.

Aplites and pegmatites rarely contain inclusions, but they are peculiar in other ways. Most important is their high mineralizer content, to which reference has already been made. The effect of the mineralizers is to make the magma a strong solvent of the adjacent rocks, so that the constituents of the latter are incorporated within it. This is especially marked where the country-

FIG. 22.—Lamprophyre dike in granite. Norway, Maine.

FIG. 23.—Lamprohyre with rounded orthoclase phenocrysts. Gailbach, near Aschaffenburg.

rocks are entirely different chemically. It may be seen in the staurolite-, paragonite-, and disthene-paragonite-schists from the neighborhood of St. Gotthard, in the garnet-rich aplites from many localities, and in the zoisite rocks from Weissenstein in the Fichtelgebirge.

Pegmatites were usually the first of the complementary dikes to form, being forced into the contraction fissures of the main rock during the last stages of its crystallization. The minerals of the pegmatites, not rarely, are simply continued growths of the constituents of the intrusive rock itself, so that *welded dikes* are formed when the boundaries between the intrusive and the parent rock are entirely obliterated. The closely related aplites are also usually

older than the lamprophyres (Fig. 24), although the contrary relationship is found occasionally.

Finally, magmatic differentiation within the dike itself produces the so-called *composite* or *double dikes*. In these the aplite and lamprophyre may grade into each other (Fig. 26), or they may be sharply separated (Fig. 26). Either the aplite (Figs. 25–26) or the lamprophyre (Fig. 19) may form the selvedge.

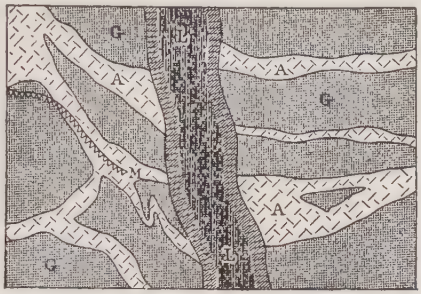

FIG. 24.—A system of approximately parallel aplite dikes (*A*) cut by a lamprophyre dike (*L*) with a granite selvedge in the Central granite (*G*). Untersulzbachkees, near the Grossvenediger.

Petrographic Provinces.—From the sequence of the intrusions and extrusions in a single igneous province, there become apparent certain laws which can be explained most naturally on the assumption that closed magma basins, in which differentiation took place, exist within the earth. The rocks of such a region (*petrographic province*), therefore, have a certain blood-relationship (*consanguinity*) which shows itself in the constant occurrence or predominance of certain chemical constituents.

FIG. 25. FIG. 26.

FIGS. 25 AND 26.—Composite or double dikes, aplite and lamprophyre. Fig. 25, showing gradual transitions; Fig. 26, with sharp contacts.

It is very difficult to explain the consanguinity of the igneous rocks of one region and their variation from those of an adjacent region if all the phenomena of vulcanism are considered the products of a still-molten earth-center. And the assumption that separate and relatively independent parts were produced by differ-

entiation from a very heterogeneous core, and that successive extrusions came from these different zones, seems rather forced. It is much more likely that differentiation takes place in local magma basins which are detached from the central core.

The Christiania basin in Norway, which is one of the most complete and most carefully studied of petrographic provinces, shows a definite sequence of eruption in a sodium-rich igneous series. The oldest formations are silica- and alkali-poor diabases. These are followed by rocks, richer and richer in soda and poorer in magnesia, iron, and lime, until nephelite-syenite, with 11.5 per cent. of soda, is reached. In the series which follows, increasing silica is accompanied by a gradual increase in potash at the expense of the soda until true granites, with 2.5 per cent. of soda, 7 per cent. of potash, and 75 per cent. of silica are reached. The series is closed by diabase, similar to that first erupted. To explain these occurrences Brögger assumed the existence of a peripheral magma basin in which diffusion led to extensive differentiation. The more insoluble constituents concentrated in the cooler, upper portion of the basin, and partially solidified. Later, the overlying strata sank by the breaking of the roof, forcing the upper part of the melt outward through fisures. In a similar manner, subsequent sinkings of the crust emptied the deeper portions of the basin with their progressively more soluble constituents, until the last concentration of very soluble materials crystallized as granite. A final sinking brought forth the last, heavy, basic remnant.

Theories of Magmatic Differentiation.—In the early days of petrography much stress was laid upon the silica contents of the different rocks, and in a tabulation of results all possible transitions from persilicic to subsilicic could be found. Based on this gradation was the oldest theory of magmatic differentiation with a scientific basis, namely that of Bunsen, which postulated the mixing of two unlike melts; (I) a normal trachytic, and (II) a normal pyroxenic, with the following compositions:

	I	II
SiO_2	76.67	48.24
$Al_2O_3 + Fe_2O_3$	14.23	29.96
CaO	1.44	11.57
MgO	0.28	6.89
K_2O	3.20	0.62
Na_2O	4.18	1.92

Bunsen assumed that these magmas existed in separate basins within the earth, and that from various mixtures of the two all of the rocks of Iceland, which were the ones he examined in detail, could be produced. Further investigations have shown that the relationships are not so simple, and that even the very forced assumption of a great number of separate magmas will not suffice.

Thus, in the place of a theory of mixed magmas, there came into

existence theories of magmatic differentiation in which the magma was regarded either as a mixed salt-solution or as a mixture of fluids of definite composition. If the magma is a salt-solution, the rock-forming minerals were dissolved primarily in the mineralizers, and magmatic differentiation subsequently concentrated certain constituents. The differentiation products, therefore, would be composed of minerals analogous to those of the parent magma, the final differentiation perhaps resulting in eutectic or monomineral products.

Rosenbusch's "kern" theory is a somewhat modified form of this hypothesis, the more important of the kerns, $(Na,K)AlSiO_4$, $CaAl_2Si_2O_8$, $RSiO_3$, R_2SiO_4, RAl_2O_3, and SiO_2, having the composition of rock-forming minerals. Rosenbusch assumed that the $(Na,K)AlSiO_4$ kern occurs nearly pure in the foyaites (magma φ) and mixed with SiO_2 in granite (magma γ). The $RSiO_3$ and R_2SiO_4 kerns appear in the peridotites (π), while a mixture of the $(Na,K)AlSiO_4$ and $CaAl_2Si_2O_8$ kerns form the granodiorites (δ) and the gabbros (ψ). Finally, a combination of most of the kerns forms the nephelite-rich plagioclase rock, theralite (θ).

The converse theories, based upon the mixing of different melts which became separated through differentiation, are fundamentally nothing more than simple inversions of Bunsen's theory.

Piezocrystallization.—Besides the factors already considered there are certain geologic relationships which, in some cases, have a modifying influence upon the separation of the minerals from a magma.

The granites of the central Alps differ decidedly in appearance from normal granites. The latter are granular rocks with unoriented crystals of orthoclase, plagioclase, quartz, and mica. The typical granites of the middle Alps have a similar, haphazard-granular texture in their central portions, but toward the contact-zones this gives place, more and more, to a parallel-banded texture, and finally to true schistosity. The mica flakes, which were unoriented in the center of the mass, here lie in parallel planes, generally normal to the direction of the pressure which folded the mountains. Except for this parallel arrangement of the mica, the two kinds of rock are exactly alike. All of them, however, differ from normal granites in many ways, both megascopically and microscopically, yet the variations cannot possibly be secondary.

For example: the biotite, which is absolutely unaltered by weathering on account of the rapid erosion at such high altitudes, usually occurs in parallel intergrowths with chlorite, and lies in sharp contact with it. In appearance it differs entirely from the mica of ordinary granite which has become cloudy by secondary change to chlorite. Further, the plagioclase, which appears perfectly fresh and transparent in thin sections, is filled with sharply-formed, unoriented microlites of clinozoisite, garnet, muscovite, and sillimanite, in some cases so abundant that a thick section of the mineral appears dull and opaque. Where the rock has a distinct parallel texture, these minerals, as well as the mica, occur in parallel layers. In many cases the feldspar crystals, plagioclase as well as orthoclase, were fractured but later reunited by a cement of quartz and feldspar upon the final crystallization of the mother-liquor. Lastly, the quartz has a typical cataclastic texture, indicating the stresses through which it passed. The original texture was naturally made indistinct by all these subsequent changes, so that phenocrysts of feldspar, where found, do not have the sharply-defined outlines and haphazard arrangement which they have in normal porphyritic granite, but lie with their flat sides parallel to the schistosity of the rock and occur in lenses, usually fine-granular at the borders. On account of their characteristic appearance in cross-sections, these rocks are called *Augen-gneisses* (Fig. 27).

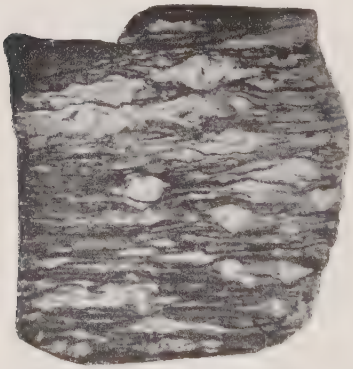

Fig. 27.—Porphyritic Central granite or Augengneiss. Scaradrapass, Graubünden.

These abnormal characteristics of the central Alpine granites were considered by supporters of the theory of dynamometamorphism (Gr. δύναμις, force, μεταμορφόομαι, to be transformed) to have been produced by secondary causes, such as orographic pressures and weathering, in rocks which originally solidified as normal granites.

It was formerly supposed that pressure, without the aid of other agencies, was sufficient to cause a rearrangement of the particles in the solid state. At the present time the rearrangement is generally considered dependent upon the latent heat and water content of the rocks. The fraction of 1 per cent. of water present in the pores is supposed to act as a concentrated solvent, dissolving the rock constituents, according to Riecke's principle, in the direction of the pressure, and building them up at right angles to this direction, thereby producing a schistose texture and other modifications. A thorough rearrangement of the solid rock without the aid of a dissolving agent is less plausible, while an increase in temperature, due to orogenic processes alone, sufficient to produce even partial fusion, is still less probable.

The central granite differs from normal granites in mineral composition and texture. It contains, namely, hydroxyl-rich chlorite, and there are great quantities of inclusions, especially in the plagioclases, of the specifically heavier calcium-aluminium silicates, such as garnet and clinozoisite. The plagioclases themselves are poorer in calcium-aluminium silicates than are those in normal granites. The appearance of the biotite and chlorite, as already mentioned, indicates their contemporaneity of formation, while the garnet and clinozoisite are intergrown with the fresh feldspar in a manner possible only for primary constituents. The chief textural difference between the central and normal granites is the parallel arrangement of the mica flakes in the former. This imparts a marked schistose texture, especially to the border-zone of the massif. Furthermore, the principal constituents are broken and fractured

in the schistose as well as in the non-schistose rocks of the entire igneous mass. Since rocks of this character are found only in greatly disturbed regions, the attempt to discover a connection between the movement and the peculiar character of the rock is justified.

The question arises: How does a cooling magma behave under intense strains developed during its solidification? Orogenic pressure, acting in a definite direction, compresses the molten mass, so that mica flakes, growing in the border-zone of the viscous magma, will develop with their long directions at right angles to the pressure. Pressure in the melt, however, does not remain oriented to a great distance but soon becomes a directionless stress. At some distance from the border, therefore, the parallel arrangement of the mica flakes is lost, and the rock acquires a haphazard (*richtungslose*) texture.

The great pressure upon the cooling mass tends, under the given conditions, to produce minerals of the smallest possible molecular volumes. In spite of the high temperature, a part of the water with which the melt is saturated goes into the constitution of minerals which would not be stable in the melt under normal pressures, and the plagioclase material crystallizes into specifically heavy calcium-aluminium silicates surrounded by a border of calcium-poor feldspar. In this way there is gradually formed a connected framework whose interstices contain the still fluid mother-liquor of the granite. Readjustments, caused by the pressure, now fracture the brittle constituents, and the mother-liquor is forced into the cracks thus formed, crystallizing in fine veins and as granular quartz-feldspar aggregates.

If large tabular crystals of feldspar had previously separated from the melt, these arrange themselves in the border-zone at right angles to the direction of pressure and become enclosed by parallel layers of mica flakes, preventing the development of crystallographic boundaries and producing lens-like forms, such as are characteristic in Augen-gneiss. The remainder of the mother-liquor finally crystallizes as a granular aggregate. If schlieren occur in the border-zones of such a molten mass, they form long drawn out layers at right angles to the direction of pressure, but toward the center of the mass they are rounded.

All the peculiarities of the central Alpine granite may be thus explained on the assumption of powerful lateral pressure operating during the crystallization of the rock, a process designated by the

term *piezocrystallization* (Gr. πιέζο, pressing together). Fig. 28 is a section showing the structural alterations from edge to center in an elongated central Alpine granite massif and its numerous apophyses in the surrounding schists. In the intruded mass itself,

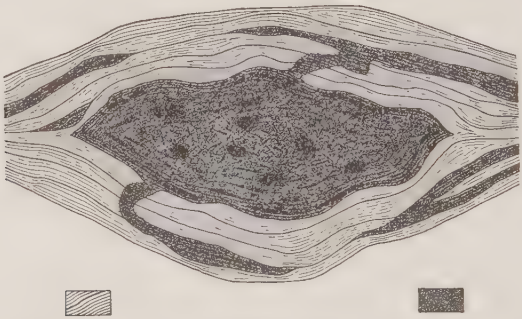

FIG. 28.—Cross-section through the Central Alpine granite massif showing apophyses resembling interbedded rocks.

which is elongated at right angles to the direction of pressure, the schistosity runs parallel to the boundary. In the dike-like offshoots, on the other hand, such a parallel arrangement cannot be recognized since the orientation of the mica plates is not dependent upon the boundary of the igneous body but upon the direction of the pressure.

FIG. 29.—Boulder from the Isar, near Tölz.

A definite proof that the parallel structure of the central Alpine granite is not secondary and produced by dynamo-metamorphism long after the solidification of the rock, is afforded by a certain boulder from the Isar (Fig. 29). This consists of a flat fragment of an aplite dike, to each side of which is attached a piece of schistose granite. The smooth surface of the aplite shows numerous narrow grooves into which biotite plates project parallel to the schistosity of the granite and perpendicular to the contact between the two rocks. The fragment appears to be part of the walls of a fissure into which the fluid aplitic mass flowed, consequently the granite must already have been schistose when the aplite, which is so closely related to it genetically and in time, was forced in. The sheets of aplite, which in so many cases are present in

the border-zones and parallel to the schistosity of the central Alpine granite, likewise show that the granite was schistose when the aplite was intruded.

The theory of piezocrystallization presupposes a close connection between a period of great folding of the Alps and the intrusion of the granite. Nowadays it is customary to regard mountain-formation and vulcanism as the results of entirely different processes, yet the fact that most folded mountains have granitic cores clearly shows that the intrusions are connected with the orogenesis. On the other hand, a connection between intrusion and mountain-building necessitates a relatively young age for the granite, for great stresses, such as those required for piezocrystallization, were probably present in the Alps for the first time in relatively recent periods.

It has been customary to regard granites in general, and the central Alpine granite in particular, as very old, at least Paleozoic, and in the determination of the age of the latter, special weight has been attached, for two reasons, to certain characteristic basal conglomerates which overlie them: (1) because the petrographic character of the previously existing rocks may be determined from them; and (2) because the less coarsely-grained sediments which occur in this region are few and usually so completely metamorphosed that their original character can be determined with difficulty.

Pebbles of granite, undoubtedly, are present in the conglomerates which directly overlie the main granite, for example the Rannach conglomerate of the Low Tauern, but the pebbles are of normal granite and differ entirely from the rock in place. To establish a connection between these two granites it has been assumed that the central massif was recrystallized by dynamometamorphism, while the boulders, embedded in a softer matrix, retained their original condition, but there is no justification whatever for such an assumption. On the contrary, the evidence against it is strong, for the innumerable aplitic beds of so-called micro-tourmaline-gneiss, which occur in the strata overlying the conglomerate, can be regarded only as apophyses of the undoubtedly younger granite. Furthermore, the cementing material of the conglomerate itself is thoroughly recrystallized and impregnated with tourmaline by contact-metamorphism.

The anomalous character of the central Alpine granite is unquestionably related to the mountain-building. Were the granite originally normal and only subsequently altered by dynamometamorphism, it might be of any age, and the metamorphism might have been produced at any period of folding and be entirely independent of the intrusions. If, on the other hand, its anomalous character is original, then the granitic intrusion and the mountain-folding were closely connected chronologically.

There are many field observations which force one irresistibly toward the hypothesis of piezocrystallization. Beside the relation of the aplite to the granite, shown in Fig. 29, and the fact already mentioned that aplite dikes occur parallel to the schistosity, there is present in many cases a noteworthy difference between these two rocks. It is true that aplites and pegmatites in many parts of the central Alps are just as distinctly schistose, and in their

interiors just as much brecciated by orogenic movements as the central granite itself, but elsewhere, as in the Mont Blanc region, the effects of piezocrystallization as well as of cataclastic action are less, even in the youngest granites. In the greater part of the Alpine region the aplites differ from the central granite in having been subjected to no mechanical stresses, and in having remained uniform rocks without schistosity, showing neither mineralogical nor structural variations from their normal habit.

The above argument may not be convincing to those who do not believe in a close time-connection between the intrusion of the aplite and the granite itself, but who think that these rocks originated, perhaps like ore-veins, from aqueous solutions within the previously cooled igneous rock. Such views, however, cannot be held by anyone who has studied the petrographic relationships. The consanguinity of granite and aplite is unmistakable, and all observations show clearly that aplite is crystalline-granular only where it was forced into granite which was still hot and in the last stages of solidification.

That the orogenic processes, at least in the main, ceased with the crystallization of the granite, is shown further by the fact that in the schist-zone surrounding the central granite of the Grossvenediger, in the High Tauern, almost all traces of cataclastic action are wanting, even in the very sensitive quartz-rich rocks. This phenomenon cannot be explained on the theory of dynamometamorphism, for according to this the surrounding schists especially should owe their crystallinity to orogenic movements, and consequently should show evidences of its action. Furthermore, according to this theory, the same processes as those which produced a cataclastic, schistose rock from the originally massive, unfractured central granite, must have altered various argillites, limestones, sandstones, and effusive rocks to crystalline schists without leaving, in the structures, any evidence of the mechanical stresses which metamorphosed them.

A consideration of these relationships shows, without question, that neither the youngest granite formation of this district, nor the satellite aplites, nor the metamorphosed country-rocks, suffered any considerable orogenic movement since arriving in the crystalline state, consequently between the intrusion of the principal granitic mass and the development of its anomalous character, no very great time had elapsed; time, that is, as measured by geologic periods.

The central granite, therefore, represents a comparatively young formation, whose intrusion doubtless was closely associated with the process of mountain-building. Although the rocks of the earth's crust were compressed by the folding, it is extremely probable that at the same time some of the molten material was squeezed out through the fractured crust. The enormous overlying load, which was greatly increased by the folding of the blocks, and the activity of the magma caused the latter to ascend through fissures in the bedded rocks, and, partly of its own accord, partly pushed, the molten mass forced itself into the weaker parts of the bedded rocks. It must not be assumed that, under such enormous pressures, there were empty spaces into which the rock-material could be poured. The magma first had to provide itself with room by

forcing apart, tearing, and raising the bedded rocks. Thus, in the course of a long period of time, the mighty masses which form the axis of the Alps gradually arose.

The so-called fan-structure of the Alps doubtless arose from this slow squeezing together of the rocks. The magma rising from below was pinched in at the base, where the strata, on account of the pressure, could not be shoved aside. The principal mass, consequently, was forced out above. This is shown in Figs. 30 and 31, which approximately represent the fans of Mont Blanc in two stages of their development.

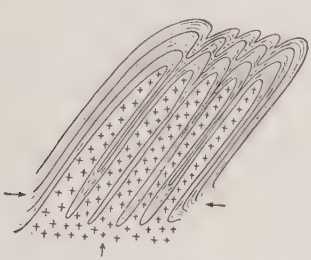

Fig. 30.

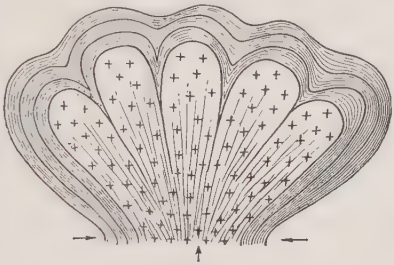

Fig. 31.

Figs. 30 and 31.—Origin of the fan structure through the intrusion of a magma during mountain folding.

Injection of the Adjacent Rocks.—The extensive mechanical results produced by the intruding mass upon the adjacent rocks clearly shows that the molten magma was not a viscous mass which was later passively pushed by tectonic processes to the place of its solidification. Contact-breccias (Fig. 32) and much folding of the country-rock near the contact and a gradation into fine fold-

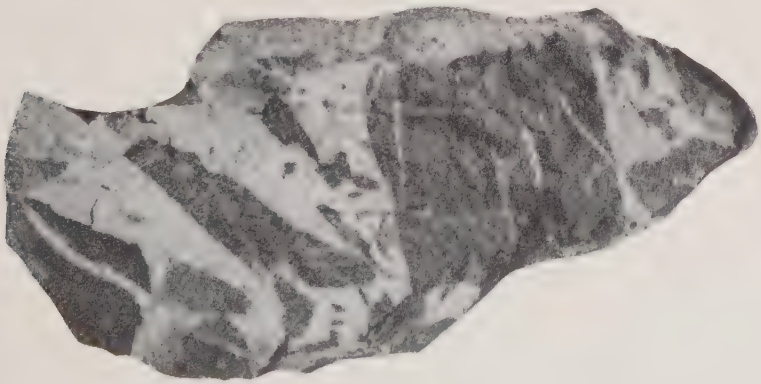

Fig. 32.—Contact breccia. Geyer, Erzgebirge.

ing away from it, show the activity of the magma. The intrusion of the magma, and especially the intrusion of its much more mobile aplitic differentiation products, into the finest fracture and schistosity planes of the adjacent rock, and the exfoliation of the schistose border and its complete saturation with molten material

(Fig. 33), that is, its injection, show this active property especially well.

The melt itself, saturated with mineralizers, may have been explosive under certain conditions. The belief that intrusive masses fill former cavities in the earth's crust, or that the igneous material of dikes was poured into gaping fissures, is entirely erroneous. The intrusion of molten masses, in the majority of cases, undoubtedly had a certain connection with orogenic processes. This may be seen, for example, in the arrangement of a series of granite stocks parallel to the chief lines of weakness of a region, or the intrusion of large granite masses parallel to the axis of a folded mountain range, yet in neither case is it probable that the magma flowed into open cavities. It is much more likely that the melt, oversaturated with gases and vapors, broke through places most

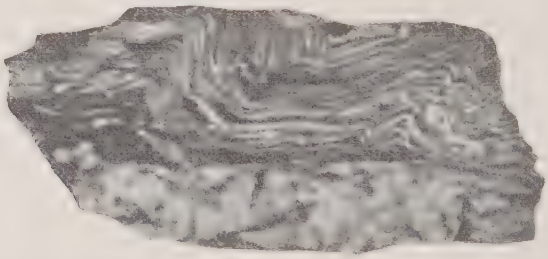

FIG. 33.—Very thin-bedded and folded injection schist. Oberpfalz.

weakened by tectonic processes and, rupturing the crust, lifted the upper strata to enormous heights. The folding of rocks already schistose caused a loosening of the lamellæ, and between these the volcanic material forced itself, principally parallel to the schistosity. This intrusion caused such an extensive tearing apart of the schist that shreds and fragments of it are enclosed in the solidified igneous rock. Where the magma forced itself in the form of a laccolith between approximately horizontal beds, the overlying strata were first attacked, and into the spaces between its exfoliating plates, the molten rock entered. Where the beds were steeply inclined, they were torn apart for great distances along the bedding, so that a rock with alternating parallel bands of granite and schist resulted. In less schistose rocks, such as limestones, sandstones, etc., or where fractures extended to considerable depths through the sediments, the intrusive masses forced their

way across the schistosity along fissures and fractures, widening them locally to true stocks.

The country-rocks of all stock-like masses are not injected to the same degree because the action is much less marked where the invaded rocks are less schistose, or at least less exfoliated. But even here the magma was forcibly intruded, as is shown not only by the wide distribution and partial assimilation of fragments

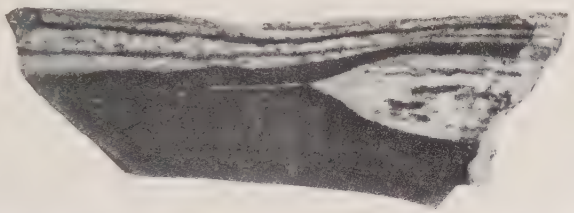

FIG. 34.—Hornfels with parallel bands of granite. Riesenberg, near Ossegg, Bohemia.

of the wall-rock in the intrusive, but also by the apophyses which in many cases extend into the surrounding rocks to great distances. Where hornfels is banded in this manner by granite and aplite (Fig. 34), it may be very similar in appearance to an injection-schist. In other places the apophyses cut the country-rock in entangled veins, or follow particularly prominent planes of schistosity (Fig. 35).

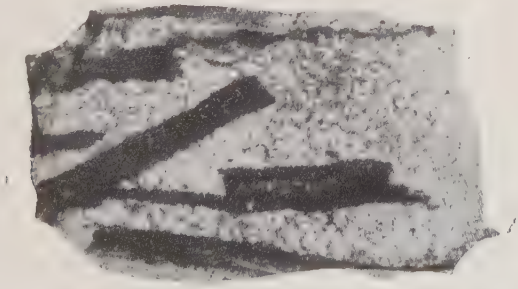

FIG. 35.—Hornfels torn apart along the bedding by granite. Gefrees, Fichtelgebirge.

The effect of the intrusive upon the country-rock depends more upon the latter than upon the former. For example, the aplites of the central Alpine schist-zone lose their typical aplitic characters where they invade granular limestones.

Where the schistose structure was well developed in the rocks, or where joints had previously been started by orogenic processes, the molten magma was usually injected into the schists to great distances. This is shown in Fig. 36, which represents a granite

mass with included fragments of greatly crumpled schist, the latter filled with aplitic material even in its finest cracks. Where such blocks occur in the border-zone they form apparently homogeneous beds which, on superficial examination, give the impression of schistose or banded rocks (Fig. 37). They have, consequently, been called gneisses, or, more specifically, banded- or vein-gneisses. The granite has had a pow-

FIG. 36.—Granite injections in the country-rock.

erful dissolving effect upon the schist on account of the intimate contact between the two, and numerous accessory minerals, such as cordierite, iron-garnet, aluminium silicates, etc., whose constituents were taken from the country-rock, occur widely distributed in the injected dikes. The intrusive rock itself may not be exposed in every case, but the injected material and the partial resorption of the schists prove that

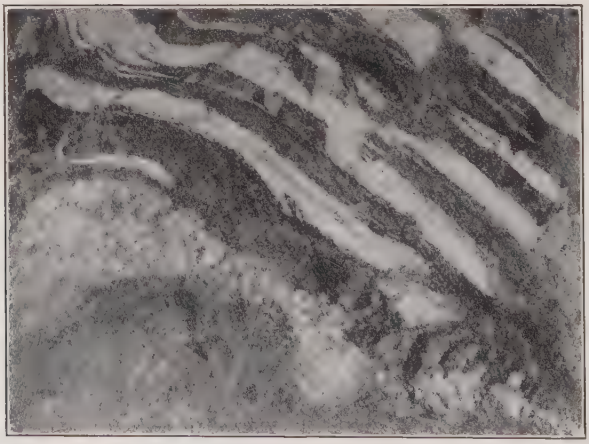

FIG. 37.—Schieferhornfels banded by granitic injections. Odenwald. (Prof. Dr. Klemm, photo.)

an igneous body must be present at no great depth. In a number of such cases, as in the Hohen Venn and in the Henry Mountains in Utah, great masses of granite which did not appear at the surface have actually been exposed at a later time by the digging of tunnels, shafts, etc.

A careful examination of contact-breccias, irregular apophyses

in hornfels, injection-schists, and partially or entirely resorbed schists, shows that they are entirely comparable formations. It is true that they appear quite different externally, yet they all originated by the same igneous processes.

It was long before the metamorphism of the so-called Archean formation was recognized as being due to contact-metamorphism or to injections and resorption by granitic intrusions. The effects of well-characterized, chemico-geological processes which are here apparent had wrongly been considered indicators of a definite geologic age, especially by French geologists. Recently, however, they recognized that in many of these gneisses the boundaries between the injected granite and the country-rock become gradually more and more indistinct until the rock presents a nebulous appearance (*Nebulite*, Fig. 38), while other extensive

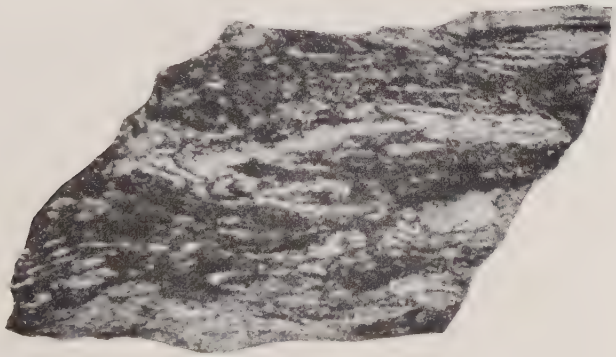

FIG. 38.—Nebulite, or schist resorbed by granite. Vilschofen, near Passau.

areas of such injection-rocks occur without the immediate presence of any igneous mass. This led to a new theory directly opposed to the former.

According to the latter view, the materials of the crystalline schists were brought under such conditions by orogenic processes that gases and vapors, either from the molten interior itself or from a peripheral magma basin, entered into them and produced molecular rearrangements, after the manner of the agents of contact-metamorphism. The action, however, was not limited to the production of new constituents from the materials of the old. In the mineralizer-saturated mass, far-reaching diffusion processes took place and gradually led to a kind of *liquation*, so that, from the originally homogeneous magma, two partial magmas were

produced, resulting, for example, in the production of alternating light and dark bands in the so-called banded- or vein-gneisses.

This theory may be regarded as a reconstruction of Hutton's view that regional metamorphism is caused by subterranean heat, a theory seemingly substantiated by recent observations on the universal distribution of tourmaline and the mineralizing action of superheated gases. This process has been called *pneumatolitic*-metamorphism, but this is rather a makeshift term used to explain occurrences in which the active agent of normal contact-metamorphism, namely the granitic intrusive rock, either is not exposed or its connection with the metamorphism is not recognized. Petrographically there are no grounds for introducing a second group of rocks, identical with that which was produced by contact-metamorphism.

Type-mixing.—The most common kinds of rock mixtures are the injection-rocks and those produced by the assimilation of older rocks by igneous magmas. Such mixtures are most characteristic, as well as most common, in granites, although they are not wanting among other deep-seated rocks. The solution of rocks which are entirely different chemically disturbs the equilibrium of the magma, and diffusion phenomena appear, leading especially to the separation of schlieren, as was described in detail in the chapter on magmatic differentiation. Many mixed-types simply represent separations produced by a saturation by mineralizers, as was shown at the conclusion of the last chapter.

The dissolving power of mineralizer-rich magmas is exemplified in pegmatites, which, in many cases, entirely change their character upon passing into chemically different rocks, so that only by their geologic continuity can the different portions be shown to be parts of the same intrusion. In many places the type-mixing has gone so far that hardly a trace of the normal pegmatite-minerals remains. The first stage in the alteration is shown by the appearance of occasional crystals of garnet, cordierite, epidote, spinel, etc.; the final stage in many cases by the production of anomalous orthoclase- and quartz-free rocks, such as are abundant in so-called gneisses. Other examples were given on page 52.

The more slowly such a mixed-rock solidifies, the more completely are the foreign constituents dissolved, while at the same time the non-uniform condition and parallel structure, which were brought about by diffusion, become more and more indistinct on account of the protracted crystallization. The resulting rock, therefore, may be quite uniform in appearance. The country-rock itself is changed by the addition of foreign constituents through the agency of mineralizers from the adjacent intrusive.

This is shown by the occurrence of tourmaline in most rocks that have been altered by contact-metamorphism. In many places there has been an addition of great quantities of new constituents, which, in the case of schistose rocks, became uniformly distributed and produced an unquestionable mixed-type. Feldspar, especially albite, is one of the most common of the introduced minerals. It occurs in certain hornstone-like adinoles, and is especially abundant and extends to great distances from the intrusive rock in albite-gneiss or *schistes feldspatisés.*

In the selvedges of dikes, and adjacent to inclusions in hypabyssal and extrusive rocks, mixed-types are widely distributed, although they are usually only of local significance. They are very common in silica-poor igneous rocks, especially in the lamprophyres. As examples may be mentioned quartz and feldspar lenticles and granite shreds in granitic lamprophyres, and olivine nodules in basalts. The latter, which probably represent portions of the magma which crystallized deep within the earth, produced considerable alteration in the rock-type when they were carried upward in great amounts by the rising magma. Silica- and alumina-rich inclusions are usually surrounded by resorption-rims which contain more glass than the normal rock. In some cases silica-rich inclusions in basalts and in other basic igneous rocks have been entirely assimilated, their former presence now being indicated only by the occurrence of glass-rich schlieren. Finally, the selvedges of lamprophyric dikes are nearly or entirely of glass at the contact with silica-rich rocks, for example sordawaldite and wichtisite in granite, but such glassy zones are abnormal in ordinary lamprophyres.

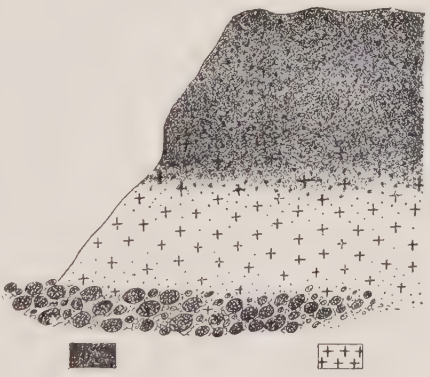

FIG. 39.—Type-mixing. Bennan Head, Isle of Arran.

The relationships where a silicic and a basic magma were mixed while still in the fluid condition are of especial interest. For example, at Bennan Head, on the Island of Arran, a sheet of quartz-porphyry, with large quartz and feldspar phenocrysts, lies above one of diabase (Fig. 39). In the latter, and especially in the lower part of the sheet, the same minerals occur as phenocrysts. Between the two extrusives there is a considerable zone of intermediate, light gray rock, consisting microscopically of an intimate mixture of the micropegmatitic groundmass of the quartz-porphyry with the ophitic trap. In spite of their perfect mixing, the two kinds of rock have preserved their individuality. In all probability the quartz-porphyry was poured out over the still molten diabase, so that the two magmas mingled at the contact, and numerous phenocrysts of quartz and feldspar from the quartz-porphyry sank into the underlying diabase. This mixture, however, of "normal trachytic" and "normal pyroxenic" magmas, in the sense of Bunsen, did not produce an intermediate type, but produced an extremely anomalous mixed-rock. The occurrence, therefore, is excellent evidence against Bunsen's mixture theory.

Szabo used the term mixed-type in a different sense from that used above. He

applied it to normal, intermediate igneous rocks; so far, at least, going back to Bunsen's theory.

Graphical Representations of Chemical Compositions.—Numerous attempts have been made to represent, in a simple way, either graphically or by formulæ, the compositions of igneous rocks. The complex nature of the bisilicates, however, prevents a perfectly clear representation.

The formulæ of Michel-Lévy, which represent textures and mineral compositions at the same time, have proved to be much too complicated for general use. His symbols are as follows:

Γ granular, Π porphyritic, α granitic, β granulitic, γ micropegmatitic, δ gabbroic, ω ophitic. For porphyritic rocks, φ spherulitic to microfelsitic, π glassy with traces of devitrification, μ microlitic with glassy groundmass.

The dark constituents are designated by capital letters; F_1 magnetite, F_2 titanite, F_3 spinel, F_4 perofskite, F_5 apatite, F_6 zircon, F_7 titanite, F_8 orthite, F_9 garnet, O olivine, H_1 hypersthene, H_2 bronzite, H_3 enstatite, P_1 aegirite, P_2 malacolite, P_3 diallage, P_4 augite, A_1 soda amphibole, A_2 green amphibole, A_3 brown amphibole, M biotite, and the light-colored constituents by small letters, l leucite, n nephelite, h melilite, s_1 sodalite, s_2 hauynite, s_3 noselite, a_1 orthoclase, a'_1 microcline, a_2 anorthoclase, a_3 albite, t soda-lime feldspars, t_1 oligoclase-andesine, t_2 labradorite, t_3 anorthite, q quartz, m muscovite.

In the formulæ the Greek letter which represents the texture is written first, then, after a hyphen, follow the constituents in the order of their crystallization, those of the first period of consolidation being marked by a vinculum, and those of the second by underscoring, as shown in the following example:

$$\Gamma\omega - \overline{(F_{1\cdot2\cdot3})OP_4A_3M}\underline{(t_{2\cdot3})(P_{3\cdot4})}.$$

This represents a rock whose texture is granular-ophitic. The minerals of the first generation are magnetite, titanite, apatite, olivine, augite, brown hornblende, and biotite, while those of the second are labradorite to anorthite, diallage, and augite. The rock is a basalt.[1]

Chemical rock-formulæ are usually based upon molecular proportions, and are comprehensive and concise. That of Osann is the one most commonly used, and rules for recalculating analyses according to his system are here given.[2] This classification is not intended as a substitute for the textural and mineralogical classification so long in use, but is intended to supplement it and make it more complete.

1. Add small amounts of Cr_2O_3 to the Al_2O_3.

2. Determine whether the percentage of Al_2O_3 is greater or less than the sum of the alkalies.

If Al_2O_3 is less than the sum of the alkalies, reduce all Fe_2O_3 to FeO by multiplying its percentage weight by 0.9.

[1] Chrustschoff proposed a modification of Michel-Lévy's formulæ (*Neues Jahrb.*, 1891, II, 225). *J.*

[2] The rules for Osann's classification given in this translation are considerably more detailed than in Weinschenk's original. The original articles by Osann are in *Tschermak's Mitteilungen* XIX (1899–1900), 351–469; XX (1901), 399–558; XXI (1902), 365–448; XXII (1903), 322–356, 403–436. See further F. Becke, *Tschermak's Mitteilungen* XXII (1903), 214; E. Kaiser, *Centralbl. f. Min.*, etc., 1904, 338. Osann's classification is to be revised and improved in the near future. *In litteris Osann.* April 11, 1915. *J.*

If Al_2O_3 is greater than the sum of the alkalies, it is taken care of in rule 7, etc., below.

3. Recalculate the analysis to molecular proportions, omitting H_2O, CO_2, F, and S.

4. Recalculate these molecular proportions to 100.

5. Let s be the number of molecules of SiO_2, TiO_2, and ZrO_2.

$$s = SiO_2 + TiO_2 + ZrO_2$$

6. $Al_2O_3 > (K, Li)_2O + Na_2O$.

(*a*) After adding Li to K, allot Al_2O_3 to all the $(Li, K)_2O$ and all the Na_2O in the proportions of one to one to form $(K, Li)_2O \cdot Al_2O_3$ and $Na_2O \cdot Al_2O_3$. Let A represent the number of molecules so formed, that is

$$A = (K, Li)_2O + Na_2O.$$

(*b*) Allotment of remaining Al_2O_3.

If $Al_2O_3 > (K, Li)_2O + Na_2O$ but less than $CaO + (K, Li)_2O + Na_2O$, the remaining Al_2O_3, after 6a is satisfied, is united in equal proportions with CaO to form $CaO \cdot Al_2O_3$. The number of molecules thus formed is represented by C. That is,

$$C = Al_2O_3 - A.$$

(*c*) If $Al_2O_3 > CaO + (K, Li)_2O + Na_2O$, add BaO and SrO to CaO and unite in equal proportions with Al_2O_3. If any Al_2O_3 still remains unused, take enough (Mg, Fe)O to satisfy it, and add this to C as a molecule of $(Mg, Fe)O \cdot Al_2O_3$.

7. $Al_2O_3 < (K, Li)_2O + Na_2O$.

(*a*) Take an amount of Fe_2O_3 equal to the remaining alkali (amount of excess of alkalies over Al_2O_3) to form the molecule $(K, Li)_2O \cdot Fe_2O_3$, and add this, as aegirite molecules, to A. The numerical value of A still remains

$$A = (K, Li)_2O + Na_2O.$$

(*b*) Excess of alkalies.

If $Al_2O_3 + Fe_2O_3 < (K, Li)_2O + Na_2O$, the excess of alkalies is to be added to A as a separate group, so that A contains the total alkalies as before.

8. The sum of all the molecules of MnO and NiO, and of the molecules of CaO not used in rule 6*b*, and the molecules of FeO, MgO, SrO, and BaO not used in rule 6*c*, is represented by F. That is,

$$F = (CaO + FeO + MnO + MgO + NiO + SrO + BaO) - C.$$

The Fe_2O_3 not used in rule 7 is recalculated as FeO and is added here.

9. Recalculate Na_2O plus $(K, Li)_2O$ to 10, and indicate the value of Na_2O thus obtained by n. That is,

$$n = \frac{10Na_2O}{(K, Li)_2O + Na_2O} = \frac{10Na_2O}{A}.$$

10. Recalculate the sum of A, C, and F to 20, and represent these proportions, to the nearest 0.5, by a, c, and f.

$$a + c + f = 20.$$

11. The rock-formula now may be written in terms of s, a, c, f, and n, as shown below. It may also be plotted on a triangular diagram whose vertices are designated by 20*a*, 20*c*, and 20*f*. The rock is indicated by the point where the three lines, which represent these values, cross (Fig. 43).

Two other values are used occasionally in certain rocks, but they are not so important as s, $A(a)$, $C(c)$, $F(f)$, and n. They are as follows:

12. Recompute (Mg, Fe, Mn, Ni)O and (Ca, Ba, Sr)O as used in F, so that their

sum equals 10, and let m represent the value of (Mg, Fe, Mn, Ni)O thus obtained. That is,

$$m = \frac{10(\text{Mg, Fe, Mn, Ni})\text{O}}{(\text{Mg, Fe, Mn Ni})\text{O} + (\text{Ca, Ba, Sr})\text{O}}.$$

The silica coefficient (k) has the following value:

$$k = \frac{s}{6A + 2C + F}.$$

As a check on the work we have $s + 2A + 2C + F = 100$.

For rapid calculation, Kaiser used the following additional formulæ. After computing the molecular proportions and reducing to 100, he determined

$$N = 100 - (s + \text{Al}_2\text{O}_3 + \text{P}_2\text{O}_5),$$
$$P = \frac{A}{N},$$
$$Q = \frac{\text{Al}_2\text{O}_3}{N}.$$

From which

$$a = 20P,$$
$$c = 20(Q - P),$$
$$f = 20(1 - Q).$$

These formulæ, with the essential formulæ of Osann,

$$s = \text{SiO}_2 + \text{ZrO}_2 + \text{TiO}_2,$$
$$A = (\text{K, Li})_2\text{O} + \text{Na}_2\text{O},$$
$$n = \frac{10\text{Na}_2\text{O}}{A},$$

are all that are necessary for a computation.

In the above formulæ $A(a)$ represents fairly accurately the amount of alkali-feldspar and feldspathoids in the rock; nephelite, leucite, sodalite, hauynite, the ægirite molecule, the potash molecule in mica, and the alkali molecule of ænigmatite and eucolite here being considered feldspathoids. No definite amount of SiO_2 is added to A to form these minerals from the alkalies, and they do not necessarily occur as such in the rock. To determine the minerals accurately one must know the relative amounts of the individual constituents and their actual compositions. The variable amounts of alkali in the micas and in the feldspathoids make the conversion difficult. In the case where $\text{Al}_2\text{O}_3 < (\text{K, Li})_2\text{O} + \text{Na}_2\text{O}$, part of the alkali unites with iron oxide to form alkali-bearing pyroxenes or amphiboles. This is usually the case only in rocks which are alkali-rich and which contain feldspathoids. In these rocks, naturally, C equals zero, and the projection points lie on the A–F line of the diagram.

$C(c)$ represents the amount of the anorthite molecule in the plagioclase. In subordinate amounts the aluminium-bearing molecules of pyroxene and amphibole are contained here, and, in melilite rocks, the gehlenite molecule also.

$F(f)$ represents the relative amounts of the dark constituents. It contains the Al_2O_3-free and the alkali-free pyroxene and amphibole molecules, the olivine molecule in olivine and mica, the akermanite molecule in melilite, the iron content of the iron ores, and the lime content of apatite and titanite.

n gives broadly the ratio of the orthoclase to the albite, or of the potash feldspathoid to the soda-feldspathoid.

k is the silica coefficient, and shows the ratio of SiO_2 to A, C, and F. To obtain

k, therefore, the value s must be divided by a number equal to the sum of the silica molecules necessary to change A and C to feldspars and F to the metasilicate.

According to this system (see Fig. 43 and rule 11) a rock may be represented by a formula similar to the following:

$$s_{59}\, a_{3.5}\, c_{12.5}\, f_4\, n_{8.3}.$$

This indicates a rock in which there is 59 per cent. (molecular) of SiO_2, while $(Na, K)_2 \cdot Al_2O_4 : CaAl_2O_4 : (Fe, Mg, Ca)O = 3.5 : 12.5 : 4$, that is, its plagioclase is rather rich in lime and forms $(3.5 + 12.5 =)16$ parts of the 20 into which the rock was divided, or 80 per cent. of the whole. The basic constituents constitute the other 20 per cent. We also have the relation $Na_2O : K_2O = 8.3 : 1.7$, that is, soda is much more abundant than potash, which was to be expected in a plagioclase rock. The rock is a gabbro-diorite.

Numerous graphic methods for representing the chemical compositions of rocks have been devised, but only the simplest will be given here. In a diagram either the

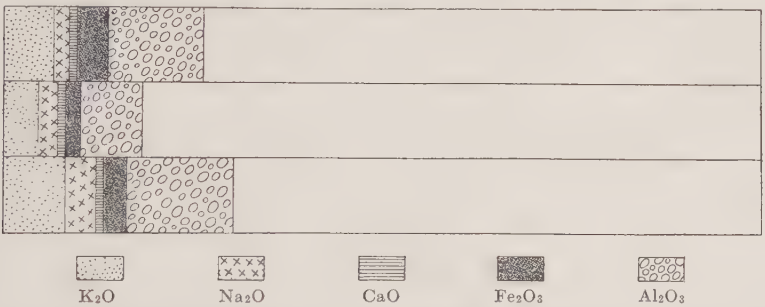

FIG. 40.—Graphical representation of the composition of a granite from Hauzenberg, near Passau. (After Rosenbusch.)

analysis recalculated to 100 per cent., the molecular per cent., or the metal atom per cent. may be used. For example, in a parallelogram 10 cm. long (= 100 per cent.) percentages may be shown in millimeters, the difference in the proportions in different rocks giving figures which enable one, with a little practice, to obtain a very good impression of the composition of the rock. Thus a granite from Hauzenberg near Passau is shown in this manner in Fig. 40. The upper rectangle represents the weight percentage, the middle the molecular percentage, and the lower the metal-atom percentage corresponding to the analysis below. This is recalculated to 100 per cent., water and the minor constituents being disregarded.

	I	II	III
SiO_2	73.83	82.1	70.4
Al_2O_3	12.30	8.1	13.9
Fe_2O_3	4.18	1.7	2.9
CaO	0.94	1.1	1.0
Na_2O	2.22	2.3	3.9
K_2O	6.53	4.7	7.9
Totals	100.00	100.0	100.0

Another diagram for representing rock analyses, suggested by Michel-Lévy and modified by Brögger, consists of four axes radiating from a center (Figs. 41 and

42). The SiO_2 content is plotted in millimeters upon the horizontal line, one-half to the right and one-half to the left of the center. The other constituents are indicated by proper intercepts on the other axes, the points so determined being connected

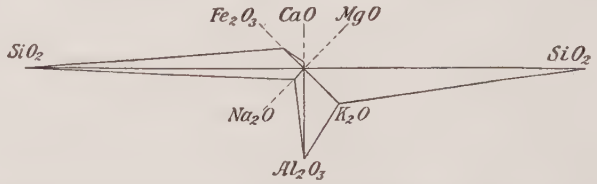

FIG. 41.—Graphical representation of the composition of the granite from Hauzenberg, near Passau. (After Michel-Lévy.)

by lines. Fig. 41 represents the percentage weights in the Hauzenberg granite, Fig. 42 those in a gabbro from Radautal i. H.

As mentioned in rule 11 above, the rock-types computed by Osann's method may be indicated by points in a triangle, the apices representing 20*a*, 20*c*, and 20*f*. If

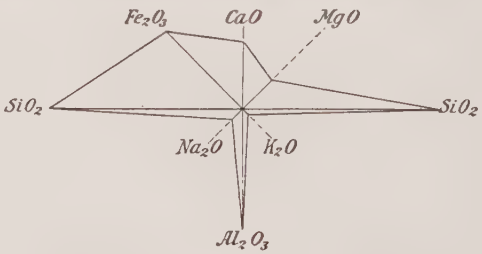

FIG. 42.—Graphical representation of the composition of a gabbro. (After Michel-Lévy.)

the values of *a*, *c*, and *f* are laid off upon the medial lines, a point is obtained for each rock of definite chemical composition. The example given on page 71, $a_{3.5}$, $c_{12.5}$, $f_{.4}$, is shown by the dot in Fig. 43.

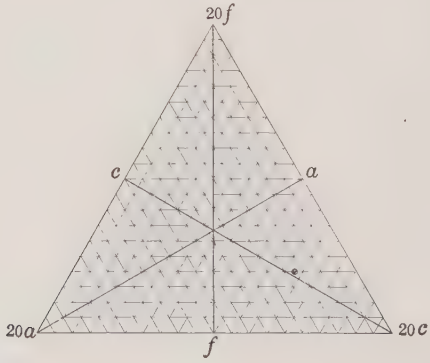

FIG. 43.—Graphical representation of a gabbro-diorite. (After Osann.)

The system of Cross, Iddings, Pirsson, and Washington, in which the chemical types and textures of rocks are represented by stereotyped "index words," is much too complicated and voluminous to be given here, even in outline.

V. ROCK WEATHERING

LITERATURE

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Weathering in General.—The term *weathering* is used to describe all alterations brought about by the atmosphere and the agents present in it, and by organisms at the surface and within the lithosphere. The action of weathering is in part chemical and in part mechanical. It primarily destroys the original rocks, whose constituents, after more or less separation by wind and water, are finally deposited to form the sedimentary rocks. Weathering acts as a leveler of the relief of the earth, and is confined to the parts adjacent to the surface.

The term *replacement*, on the other hand, includes alterations not due to the action of the atmospheric agents. The changes, therefore, do not begin at the surface, and are not confined to the

upper strata. Other changes are produced by *diagenesis* (Gr. διὰ, after, γένεσις origin), or the re-formation by the hydrosphere of the newly deposited products of weathering, during and directly after the sedimentation.

The action of the atmospheric agents is chiefly regional. It is dependent upon the moisture content and temperature of the air, as well as upon the content of chemically active agents. The latter are usually uniformly distributed but may be more abundant locally, for example near the sea or near recently active volcanoes. Also, certain agents derived from organisms are active, either by their life-processes or by their decay. There are to be distingushed, therefore, *physical, chemical,* and *organic* weathering. In most cases all of these processes act together.

Physical Weathering.—The phenomena of physical weathering are seen best in arid regions, where *insolation* (Lat. *in*, in, *sol*, sun) and great temperature differences break compact rocks into great blocks and cause the exfoliation of granite and sandstone. The great sand mass, so characteristic of the desert, is due primarily to the different behavior of different minerals under temperature changes.

While chemical weathering is much more active than physical weathering in damp, tropical climates, the latter distinctly predominates in the temperate and frigid zones. In the temperate zone the water circulating in the capillaries of the rocks is an important factor in their destruction. In fact the amount of water absorbed by a rock is taken into consideration in determining its commercial value. For example, the freezing of water in porous sandstones, limestones with clayey layers, etc., may make them friable, or may even totally destroy them. Physical weathering is especially active in high mountain regions, on account of the occurrence of great variations in temperature.

Chemical Weathering.—Chemical weathering is usually accompanied by physical and organic weathering, and is dependent upon moisture and temperature. Where the evaporation of the rainfall is greatly retarded by a thick cover of vegetation, as in the tropics, it is of great importance.

Water falling through the atmosphere takes up certain chemically active substances even from the purest air of high mountains, and while these substances are generally present in small amounts,

they are of great importance. Besides the predominating content of oxygen, CO_2 as well as traces of HCl and H_2SO_4 are always present, and even after the water has passed through fresh, sulphur-free silicate rocks, a certain amount of chlorides and sulphates still remains.

Geologists have been inclined to over-estimate greatly the importance of chemical weathering, and all the products of rock-decomposition have been continually confounded with weathering products, rendering very difficult a general conception of the complete process of rock alteration. Certain rocks undoubtedly have been more or less completely dissolved by weathering. Thus, rock salt occurs on the surface

FIG. 44.—Karst topography. Wiesalpe, Dachstein. (After F. Simony.)

only in arid regions, and the so-called "gypsum chimneys" are simply pits dissolved in fractured gypsum-rock. Limestone also is more or less easily soluble, and the water from melting snow or glacial ice, in some cases, corrodes the underlying rock until its surface resembles a stormy sea turned to stone (Fig. 44). Further, certain peculiar funnel-shaped depressions of the Karst, called *dolinas*, belong here, and the accumulations of red clay, *terra rossa*, which occur within them are doubtless the residues from the dissolved limestone. "Geologic pipe organs" have a similar origin. These are vertical cylinders which occur in limestones, especially where the surface above was heavily forested.

Recent investigations make it appear very doubtful whether all large limestone caves are due to solution. Such caves usually occur in coral limestones, and it is worthy of note that entirely analogous openings are found in recent coral masses where they represent original gaps in the reef. Like the limestone caves, the bottoms of these gaps are covered with terra rossa or similar cave-loam. Coral islands in general show such deposits, consisting of drifted-in laterite and weathered volcanic ashes and pumiceous sands. The presence of these floor deposits appears to be an argument against leaching action, for moving water would have carried away the fine mud of

which they are composed. Stalactites certainly indicate extensive solution, but they tend rather to close up large caverns than to produce them. In open spaces the dissolving power of water is lessened by evaporation, loss of carbonic acid, and the action of organisms, giving rise to the formation of sinter. All caverns in limestone, therefore, cannot be ascribed to atmospheric agencies, although some undoubtedly represent widened fissures.

The term chemical weathering, in the strict sense, is less commonly applied to the solution of entire rock-complexes than to the alteration by atmospheric agents of the primary rock-forming minerals. By its action, sterile rock is changed to fruitful, arable land, and its study is the foundation for the study of the soil.

Chemical weathering is due primarily to the action of vadose waters, and since the activity of the latter depends especially upon climatic conditions, chemical weathering, in general, depends upon climate. It is, therefore, as has already been mentioned, a regional phenomenon. Under similar climatic conditions, the same kinds of rocks everywhere produce approximately the same kinds of weathering products. It is hardly necessary to point out that chemical weathering is more intense in moist, warm climates than in those that are dry and cold, but the nature of the action and the new minerals produced differ but slightly.

Mineralogists and geologists have long been accustomed to ascribe practically all alterations of minerals to vadose waters, and this is especially true of the alteration of anhydrous minerals to hydrous. A closer examination, however, shows that numerous complicated processes which have been ascribed to atmospheric agents, actually are always intimately connected with volcanic phenomena, and that certain alterations ascribed to weathering are simply local and not regional occurrences.

For example, one of the most important of these non-regional alteration processes which has been incorrectly ascribed to weathering, is the formation of kaolin from feldspar rocks. A close examination will show a series of phenomena proving the incorrectness of former conceptions as to its origin. Kaolin always appears in very irregular, isolated masses surrounded by normally weathered granite. It is usually white and forms a marked contrast to the rust-like products of weathering. Furthermore, it is nearly or entirely free from potash, and always entirely free from apatite. The salts essential to plant growth being thus wanting, kaolin soil is extremely unproductive, differing markedly from the soil from weathered granite, which is very fertile. It is true that certain local conditions may produce a much more intense leaching than usual, whereby the residual deposits will differ from the ordinary rusty materials. Such is the case in the alterations produced in rocks by overlying peat bogs, whose organic acids, acting as reducing agents, carry away in solution all of the iron content. In this manner white weathering products, in many cases very kaolin-like in appearance, are formed, and these, without careful examination, might be identified as kaolin. The fact that the granite in the more important deposits is completely kaolinized to depths far beyond that reached by the atmospheric agents under any circumstance, and that the deposits nearly always contain new minerals (Ger. *Neu-*

bildungen) such as tourmaline, topaz, fluorite, scapolite, pyrite, and siderite, which certainly do not normally crystallize from vadose water, is disregarded; as is the fact that bog-weathering never produces aggregates having the composition and properties of kaolin.

Hereby we come to a fundamental difference between the various products of rock alteration. Kaolin and analogous products of decomposition are crystalloids, while the chief weathering products of feldspars and other silicates are unquestionably colloids or gels. So far as is determinable with certainty, normal weathering products, in the main, are amorphous, and the property of the soil to adsorb the alkalies and the alkaline earths with great ease, and just as readily give them up again to plants, is a property characteristic of colloidal substances and marks an especially important difference between the products of weathering and kaolin. Finally, if plants could remove all of the alkali and lime from a soil, leaving only a pure aluminium silicate, it could later regain these salts by taking them from solutions; kaolin does not possess such a power of adsorption.

Because the alkalies and alkaline earths of zeolites may be replaced in part, the conception of "soil-zeolites" was introduced in soil-study, but although true zeolites crystallize very readily, none that was newly formed has ever been observed in a normal soil, nor has the probability of the existence of such crystalloids ever been shown by chemical or other investigations. Substances which in the mineralogic sense may properly be called zeolites are as rare among normal weathering products as in crystallized kaolin, and the term "soil-zeolite" should be avoided, for it produces misconceptions in regard to chemical weathering. The constituents of the soil which have been so designated are, without doubt, true colloids.

Great confusion likewise has been produced in the study of weathering by the double meaning given to the word *clay*. Under this term are included secondary deposits of more or less pure kaolin as well as the finer products of true weathering. The latter material, which was brought together by running water, consists principally of the colloidal products from weathered silicates and of fragments of quartz. As is to be expected from the manner of their origin, kaolin clays are purely local occurrences which have originated from the destruction of primary kaolin deposits. The clays of weathering, on the other hand, are normal, widely distributed, regional sediments which usually differ greatly

from true kaolin in chemical composition and mineralogical character.

Finally, as the last straw, the term *laterite* (Lat. *later*, tile), which is properly applied to the normal red weathering product of the tropics, has also been used for another peculiar, secondary substance of the tropics. The latter material is composed chiefly of colloidal hydroxides of alumina and iron, and thus differs entirely from normal laterite, whose chemical composition is not greatly different from that of the original rock. From such misconceptions originated the view that kaolin represents the end-product of weathering in temperate and cold regions, while bauxite is the end-product in the tropics, where the warmer atmospheric agents had much greater chemical energy.

The principal effect of chemical weathering is the destruction of the rocks. There are formed (1) a soluble part—the weathering solution—which carries off the basic constituents of the minerals by the aid of the acids, especially carbonic acid, which are always present in vadose water; and (2) a weathered residue, remaining where the weathering took place. Since nothing is lost in the cycle of *katamorphism* and *anamorphism*, the weathered products of the primary rocks must appear again somewhere in the secondary. Thus the average composition of argillites and sandstones nearly corresponds to that of the weathered residuum of granite. The solids of the weathering solutions are deposited elsewhere, the calcium carbonate contents being almost entirely separated by organisms, while the remaining solids appear in chemical sediments such as those in the rock-salt formations.

If kaolin is due to weathering, great quantities of potash—twice as much as of soda—should have been leached from regions which have been kaolinized, for about 90 to 95 per cent. of the primary rocks are of the composition of granite. As a matter of fact, potash-salts in sediments derived from weathering solutions are very rare as compared with those of sodium. If the bauxite of the tropics were produced by the weathering of granite, approximately 7 per cent. of potash and 40 per cent. of silica, mainly from feldspars, must have been carried away. Such great quantities of potash are not found in the precipitates from the solutions, and even less can the enormous masses of dissolved silica be found. It is true that deposits of silica, separated from weathering solutions by the action of organisms, are known in all formations,

but they are exceptional occurrences and rarely reach any considerable magnitude. If the normal product of tropical weathering were bauxite, however, two-fifths of all sediments should consist of silica derived from the solutions of weathering by organic or chemical precipitation. That this is contrary to the actual facts was shown in the chapter on the formation of sediments.

The Weathering Solutions.—The material leached from the rocks by vadose waters is found in springs, brooks, streams, seas, and oceans, and from the composition of these waters the action of chemical weathering can be best studied. Waters which fall through the atmosphere doubtless always carry, besides oxygen, certain dissolved acids, which are the primary agents of chemical weathering. In all running waters, besides predominant carbonates, there are present sulphates and chlorides whose acid radicals came from the atmospheric agents and whose bases came from the rocks through which the waters passed. Meteoric water, upon evaporation, shows hardly a trace of solid matter, but this is always present in variable amounts in springs, brooks, and streams. While the destruction of the rocks by these weak agents is very slow, locally the processes may act somewhat more intensely. The increased activity of the solutions when strengthened by organic acids has already been mentioned. The weathering is most active where the surface rocks are rich in minerals such as pyrite, whose oxidation sets free great amounts of sulphuric acid. Such weathering is especially characteristic in the gossan of ore deposits.

The composition of weathering solutions varies greatly in different regions. Where the climate is humid the percentage of dissolved matter is less than in dry climates on account of the greater evaporation in the latter. The salt-pans of the deserts are simply concentrated salt-solutions whose constituents were leached from the rocks, and whose water may all disappear during long dry periods. In areas of granitic rocks in humid climates, the vadose waters are especially poor in solids, the proportion sinking to 1 : 50,000; ordinarily the percentage in springs and streams is from ten to twenty times as great. Carbonates predominate in all of these solutions, the amount averaging 70 to 80 per cent. of the total residue. The remainder consists of about 10 to 15 per cent. of sulphates, 5 to 10 per cent. of chlorides, and a very small amount of silica, perhaps 0.5 per cent. Of the total dissolved material, 70 to 80 per cent. consists of calcium-salts except in regions which are entirely granitic, 10 to 15 per cent. of magnesium-salts, and 10 per cent. of sodium-salts. The potash contents is rarely greater than 0.5 per cent. In every case, *the weathering solutions are very poor in silica and potash.*

The composition of surface waters becomes greatly modified in arid regions when the solid constituents are concentrated by rapid evaporation. Accompanying this concentration, in many cases, there is a great decrease in the calcium content, the carbonate being precipitated after becoming insoluble in the concentrated salts

solution. Chlorides and sulphates, in rather varying proportions, are here of most importance, the Chelif River in Algeria, for example, containing as much as 7 gm. residue to the liter. Of this residue, carbonates form about 2 per cent., sulphates over 50 per cent., and chlorides 40 per cent., corresponding to 25 per cent. each of calcium- and magnesium-salts, and the remainder of sodium-salts. Here, likewise, silica and potash are of no importance.

Evaporation increases the salt content of the true salt-seas of the steppes until the waters are saturated. Soda and magnesia are of prime importance, although they occur in decidedly variable proportions, while lime is relatively unimportant, having been almost entirely precipitated as gypsum. Bitter-seas, rich in magnesia, may contain as much as 30 per cent. of dissolved constituents. Other materials of weathering, such as the salts of strontium, which ordinarily are hardly perceptible, may occur in distinctly recognizable amounts.

It is worthy of note that phosphate plays no role in vadose waters. Practically all of the apatite of the original rocks remains in the weathered residue, from which it may be withdrawn later by vegetation. On the other hand, nitrates are here and there present. They form extensive deposits in the Chilian pampas, and represent a peculiar development of salt-pans. Their origin has been ascribed to frequent and tremendous electrical discharges which oxidized the nitrogen of the air.

Borax-seas and borax deposits likewise occur in deserts, but they have a somewhat different origin. They appear to occur exclusively in volcanic regions where boron-bearing fumaroles have acted upon salt deposits. The not uncommon cementation of desert sediments with silica, however, is to be traced to vadose waters, whose small silica content was precipitated in the general concentration of the weathering solutions. By far the most silicified rocks, however, were altered by silica-rich juvenile waters, and not by solutions of weathering.

Running waters carry their dissolved constituents to the ocean, and thus, by the continual addition of solutions, even though very dilute, and the evaporation of pure water, they have gradually become perceptibly salt. Although the entering waters come almost exclusively from humid regions, the composition of the sea water differs entirely from the weathering solutions brought in. Most noteworthy is the almost complete loss of carbonates. These were partially removed by precipitation as oolite when the solution was sufficiently concentrated, but in the main they were deposited as *organogenic* sediments, having been taken up by organisms which required calcium for their hard parts. The normal residue of ocean water consists of not quite 80 per cent. sodium-salts, about 15 per cent. magnesium-salts, 5 per cent. calcium-salts, and 1 per cent. potash-salts. These are combined in the form of chlorides about 90 per cent., and sulphates 10 per cent. The chief constituent is sodium chloride, although in ordinary weathering solutions it is of slight importance.

Exhaustive investigations of weathering solutions show with absolute certainty that normal weathering has never altered granite to kaolin, nor even to bauxite. This is in harmony with the conclusion already drawn from geologic relationships.

The Weathered Residues.—A study of the weathered residues leads to exactly the same result as did that of weathering solutions. This is shown by a comparison of the composition of a fresh granite, for example that from Altmittweida in Saxony (I), with that of the granite-grush[1] derived from it (II).

[1] The translator has taken the liberty of using the verb *grush*, meaning to crumble down, to disintegrate, as a noun for the finely crumbled but not dust-like rock called *grus* by the Germans.

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	H_2O
I	73.43	14.38	2.19	0.22	0.68	3.03	6.07	0.96
II	73.84	14.62	1.28	0.35	0.37	1.56	5.98	2.85

These analyses show that only lime and soda have been withdrawn in any considerable amount from the rock by the atmospheric agents. The increase in magnesia in the weathered product is probably an error in the determination. The noteworthy feature, however, is the fact that the proportions of silica, alumina, and water in the second analysis are entirely different from those in kaolin. Kaolinized granite contains at least one and one-half to two times as much alumina and about five times as much water as the granite-grush above.

Granite-grush may be sorted later by wind and flowing water, and then be deposited as sandstone or calcareous argillite; the former consisting essentially of quartz, the latter of the colloidal weathering products of the rock-forming silicates. The silica content is large in sandstones, and few conclusions can be drawn from these rocks in regard to the course of the weathering of the silicates. A study of the finer material which was washed out and deposited as argillite gives better results. For example, a very plastic kaolin from Klingenberg on the Main (I) and a normal sedimentary clay from the English coal formation at Frankland (II) have the following analyses:

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	H_2O
I	49.37	30.10	3.9	.....	0.38	.....	.....	16.24
II	61.91	20.73	5.01	0.59	0.5	0.25	3.16	6.73

An inspection of these and the analyses previously given, shows without question that kaolin and bauxite are not normal weathering products. The same conclusion is reached from an examination of the chemical composition of the soils produced by organic weathering. The primary result of all weathering processes is the removal of the lime, magnesia, and soda by vadose waters. The greater part of the potash remains in the soil, to be very gradually withdrawn, though seldom entirely, by plants. The colloidal alteration products of the silicates which were formed by chemical weathering are to be recognized from the physical properties of the soil rather than by direct observation. These colloids form but very thin films upon the surfaces of the different minerals, so that a completely disaggregated granite-grush still permits the main features of its chemical composition to be clearly recognized. The potash of the feldspar is very slowly leached from the thinnest beds, and is made accessible to plants through colloidal aluminium silicates. The leached soil may be regenerated

artificially through the addition of potassium-salts, which become absorbed by the colloids, or naturally by allowing the land to lie fallow. In the latter case the potash of the smallest feldspar particles in the soil is made available by the superficial alteration of this mineral to colloids, which later give up their content of alkalies and alkaline earths to plants. The slow process of true weathering is thus entirely different from the relatively rapid and radical process of kaolinization, and this difference is shown not only by the greater or lesser rapidity of the processes themselves, but by the nature of their end-products, kaolin and colloids.

Climatic Zones of Weathering.—The difference in the character of weathering in humid and dry climates was mentioned under the heading of weathering solutions. Here the influence of hot, temperate, or cold climates upon the final character of the weathered products will be described. Qualitatively the weathering solutions are the same in all zones, and the differences in the character of the products are very small. The external rather than the internal characteristics of the weathered residues are of importance.

The intensity of chemical weathering depends upon the humidity and temperature of the atmosphere. It acts rapidly and deeply in the humid climate of the tropics, but only superficially in the arctics. The differences in coloring in different climatic zones are especially noteworthy. In the polar regions the weathered products are light-colored to white, in the temperate zone they are typically rust-colored, while in the tropics they usually have the red-brown to red color of laterite. This difference is due primarily to the extreme slowness of weathering processes in cold climates, the oxygen of the vadose waters being extremely inactive here, and the iron oxide is removed from the rocks by solutions as fast as it is formed. In the temperate zone, the iron is precipitated as colloidal iron hydroxide or rust; the higher the temperature of the surroundings, the less water in the iron hydrates and the redder the color. That the intensity of the color of any weathered rock depends upon the percentage of iron in it, is self-evident, for example a gabbro or trap normally weathers darker than a granite, but the degree of color of any particular rock-type indicates its climatic zone.

It may here again be mentioned that the name laterite is used in the tropics not only for normal weathering products, but also for peculiar deposits which consist primarily of colloidal aluminium and iron hydrates. While always local in occurrence, some of these deposits are of considerable size, and many of them grade into commercially valuable masses of bauxite and limonite. These,

however, as has been pointed out several times, are entirely anomalous formations, and while in some cases they can be distinctly recognized as alteration products of different igneous rocks, they certainly cannot be considered to be their normal weathering products. In many places analogous masses are found which undoubtedly are new formations (*Neubildungen*), being in part superficial incrustations, in part aggregates or fragments embedded in limestone. In their irregular form and their pisolitic texture, which in many cases is distinct, they resemble the bauxite deposits of the sediments of former geologic periods. In general, also, they differ from normal weathering products in the irregularity of their bedding.

Laterite, the normal weathered material of the tropics, covers a considerable part of the earth's surface, and upon much of it there is a dense growth of vegetation. The anomalous deposits, however, have a different appearance, for heavy vegetation cannot grow from soil composed of pure aluminium hydrate and quartz, since the salts necessary for plant nourishment are wanting.

The red color of the weathered material in the tropics is undoubtedly the result of a warm climate, and it is as justifiable to conclude from the red color of a sediment that a warm climate existed during its deposition, as it is from the presence of tropical flora and fauna. Similarly, very light-colored sediments generally indicate a former cold climate. The color of the weathered material in the different climatic zones, therefore, serves as an important aid in the study of the earth's history.

Chemical Weathering of Former Periods.—The course of chemical weathering, as it occurs at the surface of the earth at the present time, may be accurately followed. The question arises, may not the climatic conditions in former geologic periods have been so greatly different that ordinary atmospheric weathering yielded products which, at the present time, form only under very exceptional circumstances? The carbonic acid which is now stored in the limestones and dolomites, the carbon of organisms, and the chlorine which is present in the waters of the ocean, were all doubtless taken from the primordial atmosphere. Our present atmosphere contains about one-thirtieth of 1 per cent. of carbon dioxide, but even a very slight increase in the amount would make it impossible for the higher animals at least, to live. If all of the carbon dioxide of the limestones and dolomites and the chlorine of the chlorides had been contained in the original air, there would have been present, in far remote geologic periods, such enormous amounts of these agents, that it would have been necessary for the respiratory organs of animals to have been very differ-

ently organized. Such an active atmosphere, also, probably would have caused intense alteration of the rocks, such as occurs only locally at present.

The sequence of weathering can be followed in the oldest geologic periods with nearly the same accuracy as it can at the present time. The mechanical sediments show the composition of the residuals of weathering, while the chemical precipitates show at least the fundamentals of that of the weathering solutions. Both mechanical and chemical sediments, from the oldest Cambrian formations to the present, show the same characters throughout, consequently there is no reason to suppose that any notable change has taken place in the character of the atmosphere during that time.

Thus there is an apparently unbridgeable difference between direct observation and speculation. But this difficulty vanishes when a factor, until now neglected, is taken into account, namely the influence of vulcanism in preserving the equilibrium in the composition of the atmosphere. The carbon dioxide, brought from the interior of the earth, continues to replace that which is being stored in the carbonates and other organic sediments.

During periods of especially great volcanic activity there resulted an atmosphere high in carbon dioxide. This led to the development of unusually abundant vegetation and the reëstablishment of the equilibrium. The most extensive organic sediments, therefore, are found in connection with formations which are characterized by exceptionally intense volcanic activity; for example, the Carboniferous and the Tertiary. From such observations the conclusion is justifiable that while the amount of carbon dioxide in the atmosphere varied during past geologic periods, the proportion was never very different from that existing at the present time. So far as can be determined from the formations remaining, there never was enough carbon dioxide in the air at one time to produce the limestone formations now found.

In the same manner, the chlorine content of the atmosphere remained constant. Free hydrochloric acid is added by volcanic eruptions, the volcano Puracé in Columbia alone giving off over 30,000 kg. daily.

Organic Weathering.—The processes of organic weathering, which generally accompany and are usually intimately connected with the chemical processes, are somewhat different. Vegetation removes from the rocks, especially from the comminuted products of chemical weathering, substances which are not soluble in the atmospheric agents. Chemical and physical weathering make the constituents of the rocks more available to plants, and these, by the secretions of their roots and the coöperation of soil bacteria, extract the substances necessary to their existence—primarily

potash, lime, and phosphoric acid. Although lichens, moss, and the like are able to obtain their nourishment directly from rocks, any considerable number of the higher plants can obtain the necessary salts only from the colloidal weathering products.

Different plants withdraw the salts from the soil in different proportions, and thus, while they remove certain constituents, they produce, by the destruction of new material, an enrichment in substances less necessary to themselves. This fact is of great importance to agriculture. Where chemical weathering is slight, the nourishing salts of a soil are frequently exhausted. But this exhaustion is only apparent. When the fields lie fallow for a time, the necessary constituents are renewed during the period of predominating chemical weathering, and new parts of the soil are prepared for the use of the vegetation.

Rock-sculpture by Weathering.—Different kinds of rocks are affected by weathering in very different ways, and upon this depends, primarily, the relief and richness of form of mountains. Rocks which are rich in glass weather much more easily than those that are holocrystalline, and porous and schistose rocks and those that are internally crushed are much more easily destroyed than those that are compact. The alkali-rich silicates, especially nephelite and the minerals of the sodalite group, weather especially easily, and in many cases are dissolved out entirely at the surface of the rocks. The weathered surfaces of nephelite-syenites, therefore, are usually pitted and corroded.

In other cases, rocks which in the fresh state appeared homogeneous throughout, show different susceptibilities in different parts, and irregularities, which originally were not visible, may be brought out distinctly by the action of weathering. The weathered stratum or *alluvium* (Lat. *eluere*, to leach), therefore, does not form a cover of uniform thickness parallel to the surface, but an uneven layer; in fissures and over easily decomposed rocks the action has taken deep hold, over resistant rocks there is only a thin cover.

The rock-sculptures produced by the strong air currents of the deserts differ entirely from those produced in a warm, humid, tropical region with dense vegetation. In deserts all decomposition products are blown away, and the fresh rocks are exposed. In the tropics most of the rocks are porous and much altered to considerable depths, and in place of sharp cliffs, the forms are rounded, and fresh rocks seldom appear at the surface. There is likewise a characteristic difference between the weathered forms

on medium and high mountains, the material on the latter being carried away as soon as it is formed.

The characteristic partings and jointings of certain rocks

FIG. 45.—Platy weathering in granite. Rudolfstein, Fichtelgebirge.

(see Sec. X) have considerable influence on the weathered forms. In many cases these joints are distinct in the fresh rocks and continue downward unchanged, for example, in basaltic columns;

FIG. 46.—Rock stream. Reichenbach, Odenwald. (Prof. Dr. Klemm, photo.)

in others they appear only in the weathered rocks and then are gradually lost with increasing depth.

Jointing may be seen in many granites. At the surface the rocks have a more or less thick-platy parting (Fig. 45), but as the dis-

tance from the weathered surface increases, the joints are farther and farther apart (cf. Fig. 6), until finally homogeneous rock is reached. But even in this compact rock there are invisible parting-planes, called *rift* and *grain*, which are generally due to a parallel orientation of the minerals, and which permit easy cleavage in those directions. The rock is made porous along these planes by weathering, and the circulating water which enters brings out the superposed plates. A rock usually possesses several such jointing directions, so that atmospheric agents may round off angular fracture-surfaces, and produce spheroidal forms. If the weathered material between the harder parts is carried away, the rock may become so incoherent that apparently solid rocks are suddenly precipitated into so-called "rock-seas" or "rock-streams" (Fig. 46).

FIG. 47.—Spheroidal weathering of diabase. Fichtelberg, Fichtelgebirge. (Prof. Dr. Klemm, photo.)

The weathering agencies tend to round the edges of rocks of uniform texture where they are cut by joints, and produce forms resembling loaves of bread. This is seen in the fractured diabase in Fig. 47, and in the jointed basaltic columns in Fig. 48. On the other hand, rocks which are internally mashed, as are the central Alpine granites, fall into sand and grush upon weathering. The thinner the laminæ of schistose rocks, the more easily do they weather, consequently true schistosity assists weathering as much as does transverse schistosity.

Many phonolites show a thin-platy parting at the surface (Fig. 49), while farther down they are compact but have a rift in parallel planes. The platy partings of certain quartz porphyries, on the other hand, were not caused by weathering but by contraction during cooling, which in many cases was so great that quartz phenocrysts were sheared across in the same manner as are olivine crystals in basalt, parts of the same crystal occurring in adjacent columns.

The first indication of weathering in a granite is generally the appearance of rusty infiltration products. These may be present, not only in the granite-grush, but even in the apparently fresh rocks. They penetrate from the surface downward, as if

FIG. 48.—Spheroidal weathering of basaltic columns. Schlossberg, Aussig, Bohemia. (J. Roth.)

through fissures, and form a yellowish stain, indicating that the rock is porous, or appear in the form of dendrites (Gr. δένδρον, tree) in the joints. If the weathering penetrates deeper than usual, as in the granite of the Bavarian Forest, there may be found, beneath the upper rusty layers, completely altered sandy beds, still showing the

FIG. 49.—Platy weathering of phonolite. Black Hills, S. D. (J. D. Irving.)

original granitic texture and with still unoxidized iron, the waters having lost their oxygen before reaching this depth.

Denudation.—The forms produced by weathering are made apparent by the forces of *denudation* (Lat. *denudare*, make bare).

These, however, do not simply transport the weathered material, but they attack and wear away the country-rock by means of the fragments carried. The thinner the cover of vegetation, the stronger the denudation; therefore it is particularly great in deserts, on high mountains, and in the polar regions. The weathered forms of a denuded region differ according to the agents. Wind and continental ice denude the entire region over which they act, and are not dependent upon the slope of the surface as are flowing water and glacier ice. The denuding action of wind is called *deflation* (Lat. *deflare*, blow off), that of flowing water *erosion* (Lat. *erodere*, gnaw out), that of the sea *abrasion* (Lat. *abradere*, scratch off), and that of glaciers *exaration* (Lat. *exarare*, plow out).

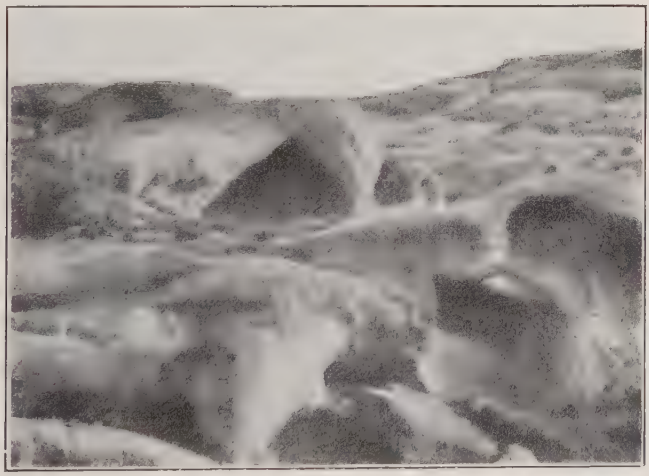

Fig. 50.—Corraded granite. Russian Turkestan. (Prof. Dr. Merzbacher, photo.)

Sand masses moved by desert storms may wear away even the hardest rocks. This *corrasion* (Lat. *corrado*, scrape together) may gnaw deep holes in uniformly granular rocks like granite (Fig. 50), or polish compact rocks, or pit those consisting of granular aggregates of minerals of different hardnesses. Furthermore, flat, arched facets may be ground on the larger fragments (*Dreikanter*), or the surface may be gouged and smoothed until it suggests that of a meteorite. This resemblance is made still greater by a glistening black crust of manganese and iron hydroxides, the so-called *desert varnish*. The wind also concentrates the larger, harder constituents of broken rocks while it blows away the more easily destroyed interstitial parts. This is seen, for example, in the accumulations of flint nodules, fossils, etc.; the so-called *desert pavements*.

The residual forms produced by the wind depend upon the character of the rock. Compact rocks form steep, high cliffs, sharp needles, and jagged peaks, while horizontally bedded rocks become flat table-lands with surfaces of harder strata. If these are cut by sharp fissures and cross-fractures, typical bad-land topography with characteristic mushroom forms, results (Fig. 51).

FIG. 51.—Bad-land topography. Washakie Basin, Wyoming. (After C. King.)

FIG. 52.—Bosses, Grimsel hospice. Bernese Oberland. (Photo. Photoglob.)

Denudation by continental ice, like that by wind, is regional, but the forms produced are entirely different. The whole weathered surface is removed by the

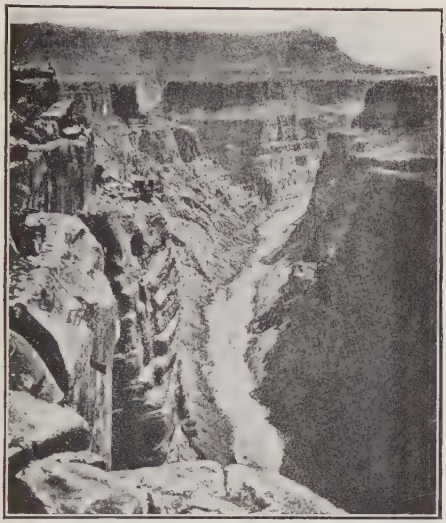

FIG. 53.—Grand Canyon of the Colorado.

former, and the fresh rock takes on predominatingly rounded forms, the so-called *roches moutonnées* (Fig. 52). While fresh rock may be exposed by the sand-blasts of

FIG. 54.—Trass deposits. Tönnisstein, Brohltal, Eifel. (After Völzing.)

the desert as well as by the plowing action of continental ice, the surface exposures are different. In one case they are covered by the peculiar desert varnish, in the other polished and striated by the scouring of the ground-moraine. In neither case are the

new deposits confined to the valley bottoms; they also occur as sand-glaciers or moraines high up in the mountains.

Glacial action is more local and is generally confined to valleys. It produces erosion forms analogous to those formed by continental ice. In each case there is a

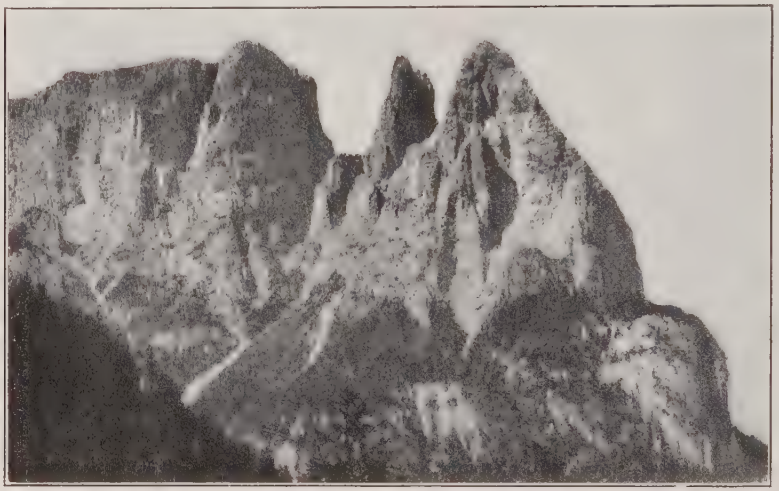

FIG. 55.—Dolomite ridges. Bozen.

tendency to round corners, smooth out the sharp and hard lines of the landscape, and widen the valleys.

Denudation by means of flowing water is entirely different. Here everything moves downward, and deposition is confined to the valley bottoms. Where there

FIG. 56.—Silicified baryte dike. Borstein, Reichenbach, Odenwald.

is a great difference in elevation between the upper stream course and its mouth, the neighboring rock may be cut into deep valleys and gorges. An extreme case is the grand canyon of the Colorado (Fig. 53) which has a depth of more than a thousand meters. Especially steep are the walls of water-cut channels when the materials of

which they are composed consist of porous deposits of clay or tuff, such as the porous tuff deposits of the Eifel (Fig. 54), or the loess.

Streams with a lower gradient have broader valleys with great masses of talus at either side, and the larger blocks of this fallen material usually preserve their angular outlines, in contrast with the rounded bowlders formed by ice or flowing water.

Rocks which are hard and able to withstand chemical weathering are least cor-

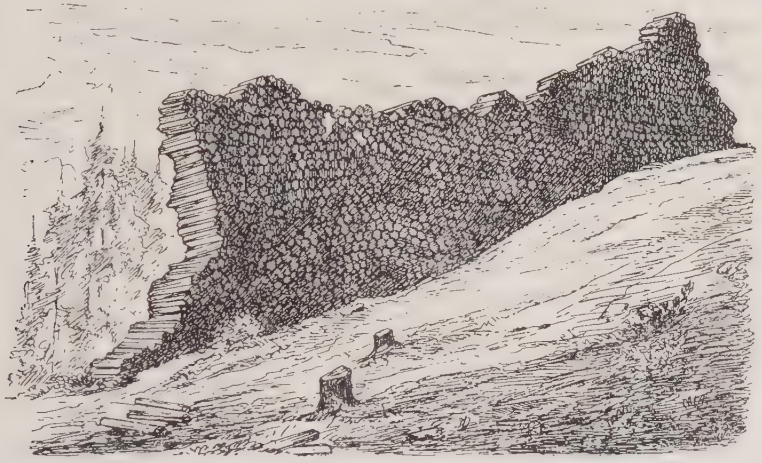

FIG. 57.—The devil's wall, a denuded basalt dike. Oschitz, Bohemia.

roded, so that, after denudation, they stand out in great jagged peaks, like the dolomites of South Tyrol (Fig. 55). Even at lower altitudes, pegmatites and massive quartz dikes stand out prominently above the surrounding weathered material (Fig. 56), and serpentine forms projecting knobs. Locally, also, steep-walled dikes of basalt may stand out from more friable country-rock, an especially grotesque dike being shown in Fig. 57. Lamprophyres generally weather more easily, and therefore ordinarily appear as shallow trenches instead of as ridges.

FIG. 58.—Map of the south coast of the Isle of Arran. The trap dikes are prominently exposed by abrasion.

The effects of abrasion are similar to those of erosion but naturally are confined to seacoasts. The breakers act upon the softer rocks first. If these are horizontal, they are undermined; if they run at an angle to the coast, they are cut into deep bays. An excellent example of the latter is shown on the south coast of the Isle of Arran (Fig. 58), where hundreds of trap dikes stand out like walls above the easily weathered sandstone, and extend far into the sea.

VI. THE NATURE OF THE SEDIMENTS

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Composition of the Sediments.—The materials forming the sediments are derived both from the weathering solutions and the weathered residues. If the weathered residues come under the influences of the transporting forces which act at the surface of the earth, they are carried away to form the various mechanical sediments, *œolian* (Aiolos, God of the winds), *alluvial* (Lat. *alluvius, ad*, against, *luere*, to wash), or *glacial* (Lat. *glacis*, ice), depending upon their mode of transportation by wind, moving waters, or ice. True *chemical sediments* are formed from the weathering solutions by simple concentration, while *organogenic sediments* originate by the action of organisms upon such solutions.

Since sediments are derived from the destruction of *primary rocks*, they are also called *secondary rocks*. There is a marked difference between the chemical compositions of igneous rocks and sediments, due to the separation of the former by chemical weathering into a residuum and a solution, and the subsequent mechanical separation of the residuum into deposits of different-sized grains. This difference is especially marked in rocks derived from solutions, but it may be clearly seen, also, in most æolian and alluvial sediments. In glacial deposits it is much less strongly developed, since here chemical weathering is of slight importance, and transportation, in general, produces no sorting of the material. Sediments may have approximately the composition of igneous rocks where the weathered material is deposited in slowly moving waters near the original locality, or where porous volcanic ejectamenta are deposited by so-called mud-flows. Such sediments, however, are only of very local significance. In general, the difference is very marked, and normal sediments of all groups differ decidedly in composition from normal igneous rocks.

Mechanical Sediments.—Mechanical sediments are derived from the weathered residues, therefore their compositions, on the whole, are alike. The transporting agents separate the material, primarily, according to size of grain, and upon this a classification of mechanical sediments may be based. The finest particles of the weathered residues, which hardly reach $\frac{1}{10}$ mm., are called

dust, or if wet, *mud*. They form the *pelites* (Gr. πηλός, mud). Since they consist chiefly of the clay-like weathered products of the feldspars, they are also called *argillites*. The grains of coarser material or sand, may reach several millimeters in diameter, and when solidified are called *psammites* (Gr. ψάμμος, sand) or *sandstones*. Still coarser material is called *gravel*, and this grades into very coarse *rubble*. The few sediments composed predominantly of these coarse materials are called *psephites* (Gr. ψῆφος, a pebble), or *conglomerates* (Lat. *conglomerare*, to heap together).

Among the constituents of the weathered residues, the colloidal alteration products of the feldspars are of especial importance. These, together with extremely fine, sharp, and angular fragments of quartz and other minerals, compose the argillites. Unweathered remnants of feldspars, other than microcline, are rather rare.

Normal argillites, in the main, consist of the material usually called clay, and an examination by polarized light shows that even very compact rocks consist predominantly of this amorphous substance. Where the first stages of an inner molecular re-arrangement can be recognized, this clay-like substance shows a crystalline, micaceous character. At the same time minute crystals of rutile, so-called *clay-slate needles*, and small, but doubtless authigenic, prisms of tourmaline, are usually also developed. In unmetamorphosed argillites, neither clay-slate needles nor the mica-like constituent of the clay occurs; and if, here and there, tourmaline appears in such rocks, it is in the form of sharp, angular fragments, and not in the delicate crystals of the metamorphosed rocks.

The weathered residuum, when wind or water has removed the finest dust, consists predominantly of quartz grains, and when consolidated it forms the sandstones. Megascopically these rocks, essentially of rounded grains, are typical of all clastic rocks. Chemically, by their exceedingly high silica content, they are farther removed from the composition of igneous rocks than the argillites.

Besides quartz grains, sandstones contain variable, usually rather small amounts of a cementing material. In the argillaceous sandstones this cement is made up of fine weathered material like that which forms the argillites, and it usually contains a considerable quantity of fine quartz splinters, sharp and angular in alluvial sandstones, but showing in æolian formations a certain rounding of the edges of even the finest fragments.

The siliceous cement of quartz-sandstones may have originated in various ways. Relatively rarely does it show the effects of mashing, and rarely are distinct organic remains preserved. It is usually crystalline, in some cases appearing as extremely fine-grained interstitial matter between the rounded quartz grains, in others as a transparent continuation of growth of the more cloudy, clastic quartzes (Fig. 59). This siliceous cement is generally the result of diagenesis. The mechanical sediment may have originally carried siliceous organisms whose amorphous silica was dis-

solved by the circulating water and later crystallized, or the silicification may have been produced by the concentration of weathering solutions. In other cases the siliceous cement has the fibrous appearance of chalcedony; in still others it consists of opal, showing that the silica was introduced by hot juvenile waters.

The calcareous cement of calcareous sandstones is probably chiefly of organic origin, and is derived from the weathering solutions. Its organic character, in some cases, may still be recognized; in others the mineral has recrystallized and forms a coarse aggregate between the rounded quartz grains.

The marls[1] have a composite character, but are predominantly mechanical sediments. They consist of clayey and sandy material, and in some transition types contain a considerable admixture of organic materials and constituents of the weathering solutions, etc. While the weather-resisting minerals of the primary rocks are not rare in argillites and sandstones, they are especially common in these transition members. Thus the mica-marls are characterized by great amounts of muscovite and bleached biotite, and from them a considerable amount of tourmaline, staurolite, garnet, epidote, iron- and titanium-minerals, and chlorite may be separated by means of heavy solutions. The loess deposits are somewhat analogous.

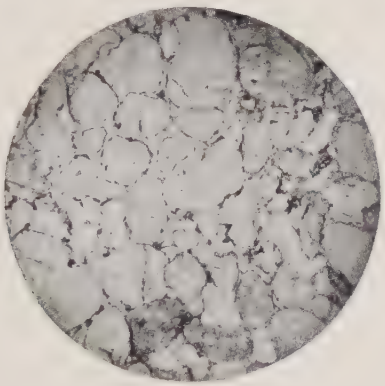

FIG. 59.—Crystal sandstone. Erbach, Odenwald.

Finally, in all mechanical sediments there are found fresh crystals of apatite, more or less cloudy zircons, and very cloudy and altered crystals of monazite and xenotime, the latter having a fresh appearance only in those kaolin-sandstones which were deposited near the source of the material. In recent oceanic deposits there occur, here and there, very fine particles of pumice and other constituents of volcanic ash. These were probably also originally present in the fossiliferous sediments but were destroyed by the rock-forming processes. Furthermore, small particles of a chondrule-like formation which have been found may be meteoritic dust.

The only constituents of the mechanical sediments which have crystallized *in situ*, other than the quartz and calcite already mentioned and local occurrences of gypsum and rock salt, are a few minerals which were modified and altered by volcanic action during the formation of the sediments or after their consolidation.

Æolian Deposits.—Æolian deposits consist of weathered material transported by wind. A prerequisite for their formation

[1] Marl is here used in the loose sense of calcareous sediments. *J.*

is a region devoid of vegetation, such as a seacoast, an area left bare by the retreat of a glacier or continental ice, or a desert. The action of the wind produces a complete sorting of the material according to size of grain. The larger fragments are only slightly moved but are more or less corraded by the wind-blown sands and take on triangular forms. These *Dreikanter* are especially characteristic of the lowest horizons of desert deposits.

The smaller sand grains are removed from the coarser detritus during violent sand-storms, and as the force of the wind decreases, a further separation takes place. Within the desert itself, grains mostly of uniform size, are deposited. This desert sand is yellow to red in color, and in many cases is heaped up to form dunes in which a bedding may be developed through the varying force of the wind and the consequent deposition of coarser or finer material. On the windward side, the dunes have a slope of 10° to 20°, and on the lee side one of approximately 30°. Where several such

FIG. 60.—Development of cross-bedding by the erosion of dunes. (After J. Walther.)

dune formations are separated by horizontal deposits (Fig. 60), they show the *cross-* or *diagonal bedding* which is so characteristic of numerous æolian sandstones. This is also found, though much less extensively, in fluviatile deposits, which are confined to stream courses.

Dune sands show *ripple-marks* (Fig. 61) at right angles to the direction of the wind. These consist of small, wave-like troughs and crests, which differ from regular wave-furrows of the seashore primarily in having numerous ramifications.

The finest dust and flaky and mica-like minerals are carried by the wind far beyond the area of the actual desert. They eventually fall among the steppe grasses, which continue to grow through the increasing depth of these deposits. Thus originated extensive and practically unstratified *loess* beds, whose peculiar porous structure and vertical cleavage are to be ascribed to the growth of these grasses. Massive deposits of loess, consequently, where cut by canyons, characteristically show high, vertical walls.

The fact that the very finest quartz-grains are usually distinctly rounded in the loess, is indicative of its æolian origin; similar material transported by water would have remained angular.

Organic remains are rare in the deposits of the desert itself, but may be very abundant in oases; and land snails, etc., are widely distributed in steppe deposits. Diagenesis, which is absent from true desert deposition, causes a concentration of the calcium content in the loess-kindchen and in the vertical root-tubes of plants in the loess.

Various salt deposits are formed by the evaporation of the weathering solutions in deserts and steppes, the soil being in many cases so thoroughly saturated with salt that hopper-crystals of considerable size are developed. Considerable amounts of other salts, usually very impure through admixture with wind-blown sand, also occur in the salt-pans. When such deposits are solidified they are known as *salt-pelites*, and are usually much brecciated by alternating dessication and re-solution by sporadic rainfalls.

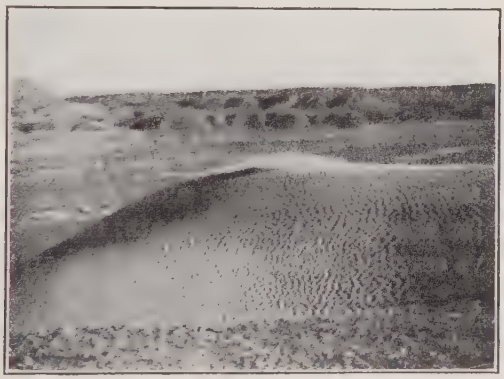

FIG. 61.—Ripple-marks. (After W. Cross.)

It is worthy of note that among the sediments formed immediately after the retreat of the ice in all glacial periods of considerable extent, similar æolian deposits occur. The reason for this is that when the anticyclonic system of winds, which originates over the center of large and much elevated continental ice areas, descends at the periphery of the ice, it becomes warmer and moisture absorbing. It is the glacial Foehn. Upon the retreat of the ice, the ground-moraine, which is free from vegetation and so porous that the water sinks into it, is laid bare, and there is thus developed a true desert climate as a result of glacial activity.

At the seashore the relationships are similar to those in the desert. The wave removes the finest silt while the wind, during ebb tide, carries away the finest sand. The latter, which is generally lighter in color than desert sand, is carried far inland and is heaped up in shifting dunes like those of the desert.

Alluvial Deposits.—Various mechanical sediments are deposited by moving water, and stream or *fluviatile* (Lat. *fluvius*) sediments are to be separated from those that are *marine*. On account of their mode of origin, the first are local in their occurrence and the latter regional.

The fluviatile deposits carry, primarily, the coarser and the specifically heavier constituents of the weathered rocks. The nearer they lie to the source, the less they are rounded, the weaker the force of the water, the less the separation into different constituents. With farther transportation the coarser detritus is first rounded, then the finer. The very finest materials suffer no rounding, even when transported great distances, and in the clay-like sediments of the ocean they are still angular. In swiftly-flowing streams, the weathered products are sorted, and the deposits, in spite of the increased flow of water, are progressively finer from the source to the mouth. With decreasing swiftness, sand, and finally mud is deposited. A stream which has lost its transporting power carries into the sea only the finest particles which are suspended in the water and which give to it a cloudy appearance. This colloidal material itself is rapidly precipitated by the catalytic action of the salt of the ocean, and leads to the formation of deltas and the continental shelf. Only traces of the very finest materials are carried into the open sea, and there the deposition of mechanical sediments is extremely slow. Lakes along a stream course act as settling basins for the coarser constituents; the out-flowing water, therefore, always carries much finer material than the in-flowing.

Fluviatile deposits show some bedding, due to the varying transporting power of the stream. This carrying power increases during high water and decreases during dry periods, so that the normal structure is not parallel but irregular, and shows sudden changes in direction. The resulting cross-bedding is similar in appearance to that seen in sand dunes.

Flowing water in many cases concentrates certain hard or heavy constituents of the rocks. Thus a pure quartz-conglomerate may be produced from the detritus of a granite which is only here and there cut by compact quartz dikes, the quartz fragments being much more resistant than the remainder of the decomposed rock. Again, rich pockets of precious stones or metals, concentrated from rocks which in themselves are poor in these constituents, may develop in depressions in the underlying strata.

Marine deposits may be divided into several groups. Of these the first is that of the true *litoral* (Lat. *litus*, coast) zone in which the influence of tides, surf, and waves is noticeable. On precipitous coasts the rocks are undercut by the waves and boulder strands are formed. The enormous force of the waves causes abrasion, and even the largest blocks are rolled one over the other, and are rounded and fragmented, while at the same time the material is sorted according to size. Seaward from the boulder-beach is one of gravel; then comes one of sand which itself may

show local accumulations of heavy minerals, such as garnets, magnetite, etc. Furthermore, the waves carry away the finest constituents, while during ebb tide when the beach is exposed, the winds remove the smaller grains from the washed-out sand and carry them landward as clay-free dune-sand. The solidified deposits of the litoral zone, therefore, are conglomerates and sandstones, and they may contain remnants of both land and sea organisms. They indicate transgressions of the sea.

Following each other in close succession from coast to open sea are transitions from gravel, through sand, to mud and ooze. This continental mud, in many places, is of a blue color on account of the iron sulphide or carbonaceous material which it contains, and it has been named the *blue-mud*. In other places it is colored green by glauconite and is then called *green-mud*. This passes over, by an increase in the amount of glauconite, into true *glauconite-* or *greensand*. Mingled in the continental mud are the cloudy constituents of river water and the fine materials washed out of the sandy beach. Fine grains of quartz are still everywhere present in these deposits, and in many cases they contain the remains of plants and animals, and beds of phytogenic and zoogenic limestone.

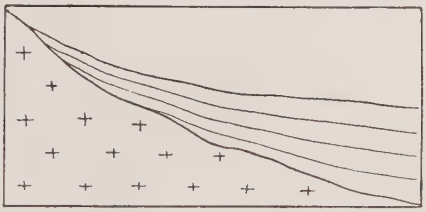

FIG. 62.—Cross-section through deposits around the continental shelf.

In true deep-sea deposits, finally, red clay predominates. This is usually without coarse constituents but contains much decomposed volcanic ejectamenta, and, in places, is completely decalcified by diagenetic processes. In other places, however, these deposits are replaced by zoogenic or phytogenic calcareous or siliceous oozes. Sea deposits are generally distinctly stratified. The original bedding runs approximately parallel to the configuration of the underlying ground, therefore many offshore deposits are far from horizontal (Fig. 62); for example, sediments deposited against coral reefs are characteristically inclined.

Direct bedding originates through successive depositions of different kinds of sediments. Every abrupt change in the nature of the sedimentation causes a sharp change in the deposit; a gradual alteration produces a transition rock, while uniform deposition leads to homogeneous sediments. The plane of separation between the different beds, in many cases, is marked by an extremely thin coating of a different character from the rest. *Indirect bedding* is produced when finer or lighter constit-

uents are washed out of previously deposited material and later sink down upon the coarser particles.

Glacial Deposits.—The chemical compositions of glacial sediments are nearer those of the original rocks than is that of any other sediment, because they have undergone but little chemical weathering, and the movement of the ice has produced little sorting of the material.

In glacial sediments there occur boulders, in some cases as large as a house, embedded in the finest till. This great difference in the size of the components, and the lack of bedding, are the

Fig. 63.—Earth pillars. Ritten, Bozen.

most marked characteristics of these deposits, especially since they are the cause of a peculiar type of erosion in formations which have been somewhat hardened by diagenetic processes. In such cases the fine material is not uniformly washed away by rain but remains untouched where it is protected by projecting covers of larger blocks, giving rise to tall pillars or earth-pyramids (Fig. 63). Glacial deposits of different geologic periods are petrographically similar on account of this mingling of fine and coarse material and the mingling of polished and striated pebbles of the ground moraines with angular blocks from the surface of the ice.

The occurrence of striated and scratched boulders is usually looked upon as a criterion of glacial activity. But such striations may be formed also by landslides, and not infrequently do the brecciated materials of faults carry polished and scratched blocks, so-called pseudo-glacial boulders. The extent of such formations, however, is limited when compared with true glacial deposits.

Chemical Sediments.—The chief constituents of the weathering solutions are carbonates, sulphates, and chlorides of the alkalies and alkaline earths, and these, therefore, are also the chief constituents of the chemical sediments. Since these sediments primarily were crystallized from solutions, they generally have a crystalline texture, but they may be distinguished from crystalline rocks, in the true sense, by their constant content of clastic constituents.

The carbonates of the alkaline earths, which greatly predominate in normal fresh water, are soluble with difficulty on the one hand, and are largely used up by organisms on the other, so that they never concentrate in great quantity. Limestones and dolomites, therefore, are of rather subordinate significance among chemical sediments, and the ocean is enriched in carbonates only where carbonated fresh water flows into it. Perhaps a direct separation of the calcium carbonate can take place under such conditions; very much oftener, however, it is the result of precipitation caused by the action of ammonium carbonate from decomposing organic matter upon the calcium sulphate dissolved in the water. At any rate, the separation of calcium carbonate by living organisms is of much greater importance in the formation of sediments than is its separation by purely chemical processes.

Recent investigations have shown that calcium carbonate crystallizes in the form of calcite, usually as very fine ooze, in water which is but very slightly salt. Such a mode of origin is assigned to limestones, such as those at Solenhofen, which are exceptionally compact and which show hardly a trace of crystalline structure even under the microscope. In very salt water, however, the precipitated calcium carbonate always takes the form of aragonite. This usually crystallizes radially or concentrically around minute foreign bodies, such as algæ, etc., which were floating in the water, and forms the small spheres, rarely larger than pinheads, which are the chief constituent of oolites.

Aragonite formed in salt water thus appears to be an important primary constituent of rocks, yet sedimentary rocks consisting of aragonite are very rare to say the least, for upon the subsequent

removal of the salt, the aragonite, which represents a labile state of the carbonate, was re-formed as calcite. At the same time the original texture of the rock (cf. Figs. 5 and 6, Pl. VI) gave place to one which was more crystalline.

Fresh-water limestones, calcareous sinter, calcareous tufas, stalactites, etc., are calcareous chemical sediments precipitated from fresh water by means of algæ, moss, and the like, which withdraw the carbon dioxide from the dissolved bicarbonates, thereby causing the simple carbonate, which is not very soluble, to separate. Such deposits from fresh vadose water are distinguished with difficulty from others that are due to juvenile springs, such as the so-called Sprudelschale of Carlsbad which is of considerable magnitude. While these deposits, especially when from hot springs, also contain aragonite in the incrustations, they have undergone no diagenetic processes which could have destroyed it. Some of these rocks from juvenile springs consist

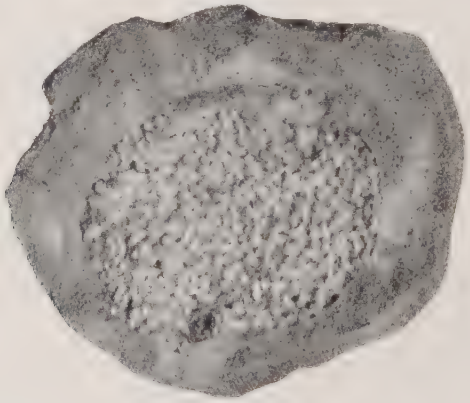

Fig. 64.—Pea-stone from Carlsbad.

of crystalline aragonite-spherules as large as peas, and called *pea-stone* or *pisolite* (Fig. 64).

Subordinate in amount, and probably derived exclusively from juvenile springs, is the siliceous chemical sediment, siliceous sinter. This is deposited especially by geysers, in many cases with the aid of certain siliceous organisms which live in hot waters. Here are to be included also many deposits from mineral springs; among them the impregnation of sands with barytes and the formation of baryte-sandstone are of some importance.

By far the most important and widely distributed chemical sediments, however, are those that were derived from the more soluble constituents of the weathering solutions, and especially from those portions which were not used up by organisms, namely sodium chloride and calcium sulphate.

Two very distinct types are to be recognized in these sediments, which occur in the enormous rock-salt formations. The first is characterized by a great regularity in the alternation of salt and

anhydrite beds, by its extremely great horizontal extent, and by the purity and often very coarse grain of the salt crystals. Furthermore, in some localities, deposits of the constituents most soluble in water, especially sulphates and chlorides of potash and magnesium, are found in the overlying beds, for example in Stassfurt.

These soluble salts are completely wanting in the overlying beds of the second group, but on the other hand they are found within the salt deposit itself, usually very subordinate in amount and irregular in distribution. The salt beds themselves show no regularity in their bedding and generally are not composed of crystalline salt but of unlaminated sandy clays strongly impregnated with salt (Haselgebirge). The beds are accompanied by anhydrite and are cut by innumerable small veins of pure salt which show by their occurrence in fissures that they are later crystallizations and not original deposits.

These contrasting characteristics of the two types may also be seen in recent formations. Where a land-locked bay is so far cut off from the open sea by a bar that the sea water can enter it only at flood tide, a strong concentration of the soluble

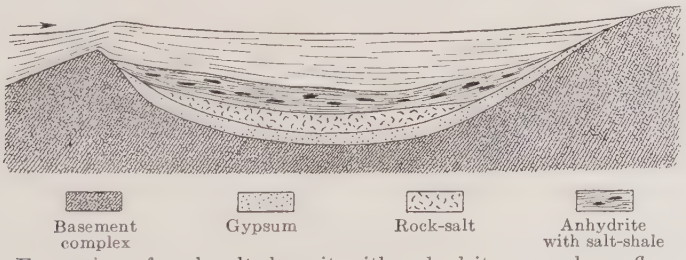

FIG. 65.—Formation of rock-salt deposit with anhydrite cover by a flow from the ocean in the direction of the arrow. (After Ochsenius.)

salts will gradually result. Calcium sulphate, which is soluble with some difficulty, is deposited first as gypsum or anhydrite (Fig. 65). This is followed by a deposit consisting chiefly of rock-salt. At a later stage a strong influx of water may come from the open sea, and not only dilute the water but bring in new calcium sulphate to be precipitated. The alternation of these two deposits may recur in this manner many hundreds of times, as in the so-called banded salt of the Stassfurt area.

The continued inflow and the reduced outflow of salt water produce a concentration of the easily soluble salts until they are finally precipitated in thin, alternating beds. In ordinary salt deposits, the upper layer is a thick, insoluble bed of anhydrite, the so-called anhydrite-hat, but in a gradually drying up bay the materials for such a bed are wanting and the easily-soluble salts already deposited can be protected from the rain only where great masses of dust from the neighboring land are blown into the dried-up basin and form an impervious cover of silt over them. This first group of rock-salt deposits may be called the *marine type.*

The second group of deposits is analogous to those of the salt-pans of the deserts. The concentrated salt water, mixed with the dust which is blown in, dried up without

lamination in the form of *salt-pelite*. During the process of drying, the deposit becomes filled with cracks, and in these the material which is leached out by the occasional rainfalls is again deposited. Since the mud dries up completely, no separation takes place between the constituents which are soluble with ease and those which are soluble with difficulty, consequently when the desert streams bring in water which is already rich in salt, the process is repeated over and over. Contrasting with the uniform conditions of deposition of the normal facies, therefore, are the very irregular conditions of the second. The latter, furthermore, is of very local importance. Most of the Alpine deposits of rock-salt belong to this class, and they are therefore spoken of as the *Alpine* or *desert type*.

It may be remarked, further, that on account of the easy solubility of the rock-salt formation on the one hand, and the great increase in volume produced by the alteration of anhydrite to gypsum on the other, great dislocations are common in these deposits, and their original forms are recognized with difficulty in many cases. Rock-salt, like anhydrite, occurs only in semi-arid regions, and cliffs of rock-salt are seen only in steppes and deserts.

Organogenic Sediments.—As already mentioned, *organogenic* (Gr. ὄργανον, organ, γένεσις, origin) sediments or *bioliths* (Gr. βίος, life) may be divided into two groups, one consisting predominantly of the inorganic skeletal parts of organisms and forming carbonaceous, siliceous, or phosphoritic rocks, the other, or *caustobiolithic* (Gr. καυστικός, burning) group, consisting predominantly of organic material such as coal, bitumen, and petroleum.

Among sediments, the calcareous organogenic sediments, in particular *zoogenic* (Gr. ζῶον, animal) limestones derived from animal remains, are of especial importance in all geologic formations, and even at the present time such deposits are being extensively formed. Calcareous sediments, in part, have the form of normal bedded rocks. Here belong, for example, shell sands which are made up predominantly of angular fragments of shells, echinoderm breccias, etc.; all of them usually formed in shallow seas. Other calcite secreting animals are *plankton* (Gr. πλανκτόν, wandering), and their remains, in part, are mingled with the mechanical sediments of the different sea-zones, in part form pure deposits, such as globigerina and pteropod ooze. The latter two consist predominantly of calcareous material. In the deepest portions of the ocean, the true deep sea, such deposits are comparatively rare, for the water of the deeps, being rich in carbon dioxide, soon dissolves the calcareous material.

In other places calcium carbonate is deposited as oyster and mussel banks, and as reefs by corals, calcareous sponges, bryozoa, and serpulites. The individual reefs, especially those of coral, may be of great size. They form fringing or barrier reefs in the

tropical seas, and completely encircle the coasts except for certain openings where the inflow of water from streams has made the sea less salt. In other cases they form the so-called lagoon reefs or atolls, the typical form of coral islands.

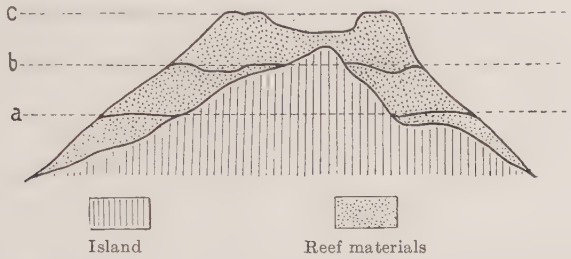

FIG. 66.—Growth of a coral reef by subsidence. *a* barrier reef, *b* fringing reef, *c* atoll reef.

Although these organisms are able to live only in shallow water, coral is found to depths of thousands of meters, the slow sinking of the ocean bottom continually renewing the conditions for their further growth (Fig. 66). In many cases the reefs have extremely

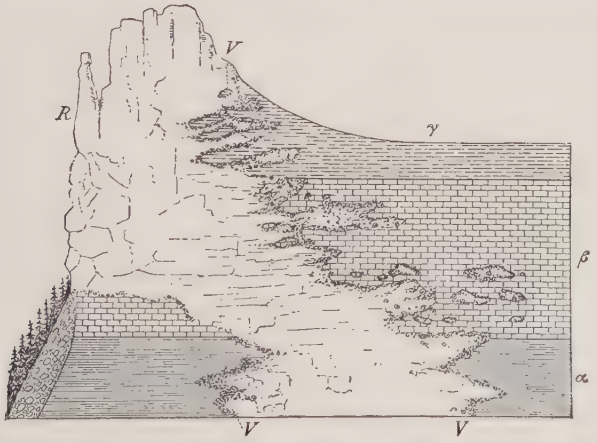

FIG. 67.—Reef passing into normal bedded deposits through a zone of brecciated material. (After E. Fraas.)

steep walls and pass over into normal bedded sediments through a zone of brecciated material (Fig. 67).

Phytogenic (Gr. φυτὸν, plant) calcareous deposits are formed in the sea by the action of algæ, especially *Lithothamnion*, *Gyroporella*, etc., and may be quite extensive. It is noteworthy that magnesium carbonate is more abundant in these formations than in zoogenic rocks, although it forms but a small portion of any organic skeletons except those of calcareous algæ, in which it may reach 15 per cent.

Organogenic siliceous sediments are in part zoogenic and in part phytogenic, the former chiefly composed of radiolaria, more rarely of siliceous sponges. It is significant that siliceous muds occur even in the deepest parts of the ocean, and locally form considerable deposits. The siliceous schists and radiolarian hornstones, derived from the siliceous muds of former geologic periods, are usually completely recrystallized, the organic silica being very easily soluble. In more recent deposits of polishing slate, kieselgur, etc., on the other hand, amorphous silica remains.

Finally, some of the phosphorites belong to the organogenic deposits. They consist of aggregates of bones of mammals and of guano and coprolites, or of limestones which have been acted upon by such material.

The second group of organogenic rocks consists of those which are composed predominantly of carbonaceous material. Their mode of origin is, to a great extent, still unexplained. Even in regard to the coals, which form the principal part of the most important group, very little is known. They are, without doubt, predominantly of phytogenic origin, and represent, in the main, the remnants of a luxuriant, primitive vegetation. Their organic structure is still distinctly recognizable in innumerable occurrences, especially in microscopical preparations from which the opaque carbonaceous substances have been removed by potassium chlorate and nitric acid.

Coal characteristically occurs in beds of rather uniform thickness, and even very thin beds may extend over great areas; the great Appalachian field, for example, covering over 135,000 sq. km. Although coal occurs in all geologic periods, it was not deposited in equal abundance in all of them, two only being marked by an especial abundance, namely the Carboniferous and the Tertiary. Extensive recent formations are unknown.

The characters of the coals of different formations are not the same. In general, the oldest coals are richest in carbon, consequently it was once thought that the process of altering wood to coal was an extremely slow one, requiring geologic periods for its completion. On the other hand it has been observed that coal beds have a higher carbon content where they are cut by faults, and that in strongly folded mountain regions they are richer than deposits of the same age in undisturbed strata. The increase in the carbon content, therefore, has been ascribed to mountain-pressure, but it is difficult to determine how far this hypothesis is correct. While the change in the coal in strongly disturbed regions is not to be questioned, it is more probable that in general the present character of the coal is due to the diagenetic processes of decay.

There is a characteristic difference in the mode of formation of bituminous coal and of the usually much less extensive brown-coal. The former, in many cases, occurs in beds which are repeated a great number of times, one above the other. At Aix la Chapelle 45 may be counted, at Mons 110, and in the Donez basin, 225. The number of brown-coal beds is usually very limited, and rarely exceeds six. The thickness of the individual beds, however, is inversely proportional to their number. Workable bituminous beds average 30 to 125 cm. in thickness, while beds of 10 meters

FIG. 68.—Petrified forest of Treuil, near St. Etienne. Dept. Loire.

are rare. On the other hand, brown-coal beds 15 to 30 meters in thickness are common.

Two methods of coal deposition have been suggested. The material may have accumulated where the coal plants grew, or it may have been transported. In the former case the fallen trees of a heavily timbered, marshy, primeval forest were transformed into coal under water, and as the deposit increased more and more in thickness, it even enclosed the still-standing trunks. As a consequence, fossil forests (Fig. 68), still upright, are found in various coal deposits, and in the underlying beds there are great rooted stumps or *stigmaria*. On this theory it is extremely difficult to explain how so many coal beds could have attained such great thicknesses. Such abundant vegetation as is necessary for the formation of coal could hardly have continued to grow in the underlying, half-carbonized masses, which must have been many meters in thickness and extremely poor in the salts necessary for plant growth.

According to the other theory, coal beds are secondary. They are supposed to

have been deposited by the action of streams which flowed through the primeval forests and carried great quantities of wood to the sea. There, possibly, the logs formed dams of such a character that they permitted the fine detritus to pass but held back bushes and tree-trunks carried in by the stream. As these became saturated with water, they sank, and were later altered to coal. It is conceivable that trees with crowns and roots, torn bodily from the mainland, might sink in vertical positions with their heavy roots downward, and thus, when wedged in by later deposits, give the impression of trees in place. Subsequently, during some particularly high stage of the water, the bar may have been torn away, and the entire deposit flooded with detritus. For a long time thereafter the floating timber may have been carried away, while the materials for conglomerates, sandstones, and shales were deposited upon the carbonizing stratum of wood. Eventually another bar formed, and the deposition of wood was renewed. An objection to this theory is the great horizontal extent of some of the coal deposits, which is out of all proportion to the size of the continent

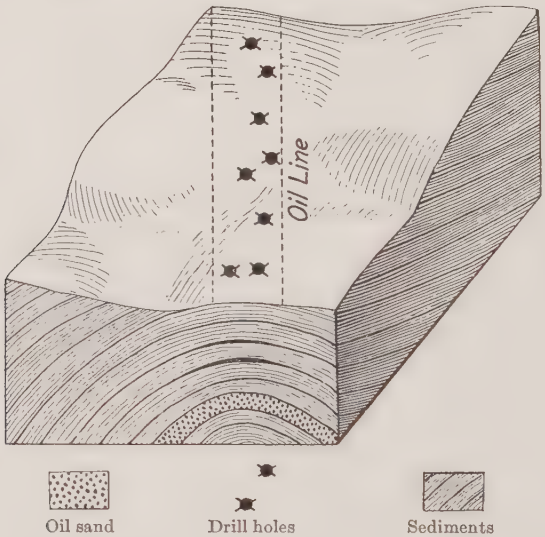

FIG. 69.—Petroleum horizon showing relation of the oil line to the anticline.

during the Carboniferous period. The problem of the origin, therefore, cannot be considered as definitely solved at the present time.

The two principal coal-measures were formed immediately after the two periods of greatest volcanic activity recorded in geologic history. This may be explained, perhaps, if it is assumed that the great amount of carbon dioxide poured out into the atmosphere by volcanic activity greatly stimulated plant growth and resulted in the deposition of the coal.

Finally the formation of bitumen and petroleum are to be considered. The relationships between the two substances are not yet very clear. One view is, that bitumen, in the main, is a residual product of petroleum; another, conversely, that petroleum springs are due to the distillation of bituminous schists. The conditions of formation of petroleum itself are not yet perfectly understood,

and it is difficult to settle the question geologically, since the oil continually changes its position within the earth and is probably never found in the place where it was formed. The geologic relationships of petroleum accumulations show certain peculiarities which make a genetic explanation no simple matter. The oil appears exclusively in the outer zones of folded regions, and the principal wells occur along so-called oil-lines. These correspond to the crests of anticlines, which are enriched by the tendency of the oil to rise (Fig. 69).

The association of petroleum with great folds of the earth's crust, and the great quantity of oil occurring in certain regions are the chief objections to the theory of its organic origin. If this theory is correct, the oil must have originated by the decay of animals or plants rich in fat, yet great accumulations of organic materials are but rarely found. It is true that bituminous shales are rather widely distributed, but they are generally not very thick, and their bituminous content is too small to be the source of the overlying petroleum. Certain provinces, for example, have produced great quantities of oil uninterruptedly for hundreds of years. Since no known sediments could by any possibility have produced so much oil, Humboldt and Mendelejew concluded that it must be of inorganic origin. They assumed that great masses of carbides and other similar compounds in the interior of the earth were decomposed by circulating water, and that the resulting hydrocarbons rose as petroleum in greatly folded strata.

The above objections to the organic theory would seem favorable to the inorganic, yet the foundations upon which the latter is based are altogether too hypothetical. While very little is known as to the earth's interior, we have no right to assume that carbides exist at depths which can be reached by circulating waters, even though carbon compounds are present in great abundance within the earth. Furthermore, the invariable association of petroleum with rock-salt, which is not explained by this theory, seems to be a strong proof for its organic origin. On the whole, the organic origin seems to be the more probable.

Diagenesis.—A comparison of recent formations with those of past geologic times shows that the rock-forming processes usually do not end with deposition, for there are characteristic differences which must have originated in subsequent periods. These alterations, caused by the circulating surface waters, begin to take place at the moment of deposition of a sediment, and continue until that stratum is withdrawn from their zone of action. These physical and chemical alterations, which may be described by the term *diagenesis* (Gr. διαγίγνομαι, to continue), are to be distinguished from the changes produced by metamorphism. Under the latter term are included those later alterations which took place in the rocks after their withdrawal from the sphere of action of the superficial agents and after they had already become geologic bodies.

The phenomena of metamorphism, which are described in a later chapter, are usually much more intense than those of diagenesis. The intensity of the latter varies considerably in different deposits. Since it depends primarily upon aqueous solutions, it is especially intense in deep-sea formations, and is only well developed in steppe and desert deposits when these come under the influence of a more humid climate.

Diagenesis in some cases consists of the solution of certain constituents of clastic sediments by the water standing above them, as in the case of ocean sediments, which are thus usually entirely free from sodium chloride, or by the leaching of the soluble salts by ground-water as in the case of alluvial sediments. In a similar manner, the water of the deep sea produces, by the great pressures there existing, a de-calcification of the sediments, so that true deep-sea deposits may be entirely free from calcium. Other diagenetic processes produce a concentration of certain constituents; for example, of manganese iron oxides in almost all recent sea-deposits, of calcite in clays as in septaria, of phosphorite and heavy spar, of pyrite and marcasite, of aluminous

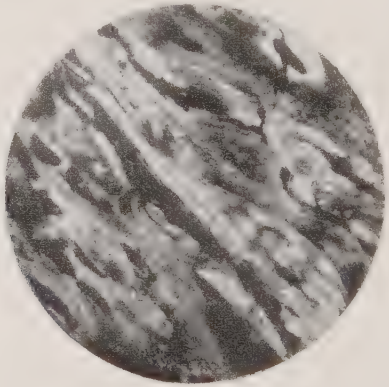

FIG. 70.—Thin section of a bone showing the complete preservation of the texture. From the Wichita beds (Permian) of Texas.

spharosiderite, and of flint and hornstone. Here also belong silicification and mineralization of organic remains.

Other diagenetic processes lead to the formation of new minerals such as glauconite, which usually forms grains in foraminifera tests, and which may be so abundant that it forms true greensand. Further, zeolites may be formed locally in sea-sediments in regions of volcanic activity, and new formations are especially abundant where mineral springs saturate deposited detritus.

At present the extent of induration of argillites as a result of diagenesis cannot be stated; recent sea-deposits, certainly, are still slimy and plastic to a considerable depth. The cementation of limestone fragments and sand by calcium carbonate, and of sandstones by silica, however, are in many cases due to simple diagenesis.

The normal fossilization of organic skeletons is also due to simple diagenesis. Calcareous skeletons, which originally consisted of chitin-like material intergrown with conchite or calcite, are of great importance in the formation of rocks. In the process of fossilization, the organic substances are first destroyed, either by complete removal, or by alteration to carbonaceous or bituminous substances. At the same time, the fine structural details of the inorganic parts are destroyed more and more by recrystallization, which always takes place when the material was originally calcite, and in some cases when it was conchite. In many cases the inorganic parts of the

skeleton are carried away with the organic and only impressions or casts remain, or the original material is replaced by a foreign substance such as pyrite or hornstone, or, in the case of foraminifera, by glauconite. Skeletons like those of echinoderms or calcareous sponges, which consist of but few calcite crystals, are best able to withstand these and all other alteration processes.

Siliceous skeletons, which originally consisted of glass-like amorphous silica, are especially likely to break up under the processes of diagenesis. They may simply alter to crystalline aggregates of quartz with only rare traces of the original organic structure, or be carried away completely by water to accumulate elsewhere as concretions of hornstone and flint, or recrystallize as quartz in fissures in the rocks. In many cases the spaces formerly occupied by the leached silica are filled by calcite.

The bones of mammals appear to be able to resist the processes of diagenesis to a great extent, so that in many cases they preserve their original texture when completely fossilized (Fig. 70).

Dolomitization, which is undoubtedly a diagenetic process, consists in the addition of magnesium carbonate to organic limestone deposits which were originally free from, or poor in, magnesia. Innumerable synthetic experiments under conditions similar to those in nature have shown that calcite cannot be altered to dolomite, while, on the other hand, aragonite and conchite take up magnesia quite readily. For this reason, apparently, dolomite is found primarily in deposits whose calcareous parts originally consisted of these unstable forms of calcium carbonate. Patches of such dolomitic alterations in recent coral reefs find an explanation in this mode of origin. There is usually a considerable alteration of the texture of the rock accompanying dolomitization, and in place of the original compact limestone, there develops a porous rock filled with drusy cavities. Further, the dolomites are distinctly crystalline, and the organic remains may be entirely obliterated or only preserved as casts.

Although the general process of dolomitization is rather well understood, the special causes for these local diagenetic alterations are not known, and the hypothesis of J. Walther that fission algæ produce chemical alterations, is not to be discarded lightly. The change from calcite to dolomite is produced by the magnesia in sea water, which is especially active when greatly concentrated and warmed, as in tropical lagoons. The alteration proceeds irregularly, and dolomite, therefore, is characterized by a variable composition. It is noteworthy, further, that only enough magnesia is used by the diagenetic process to form normal dolomite. Magnesia-rich rocks, which are transitions to magnesites, are formed exclusively by thermal processes, and therefore are generally associated with volcanic rocks.

A final form of diagenesis is that of organic substances. Coal is formed by the decay of cellulose under water. The difference between anthracite, bituminous, and brown-coal may be primary, in so far as it depends upon differences in the original carboniza-

tion processes, that is, upon diagenesis itself, or secondary and be due to the slow continuation of its formation during succeeding geologic periods.

Diagenesis of organic substances is due to fermentation. According to the theory of Lemière, three chief agencies are involved; living ferments which cause true carbonization, soluble ferments which produce masceration, and the resulting toxic substances which nullify the action of the other agents and terminate the carbonization process. No changes are produced in the coal after the cessation of the action of the ferments, so that brown-coal, thereafter, can never become bituminous. Likewise anthracite became anthracite shortly after its deposition. In the oldest coal periods the living ferments predominated, while during the formation of bituminous coal the soluble ferments were in excess.

According to other views only the beginning of carbonization is a true diagenetic process, and the enrichment in carbon will continue even in the oldest deposits until they are converted to a final state of pure carbon. It is difficult to understand why this process should continue so long, but as already mentioned, cases are known where later dislocations, etc., have increased the carbon contents of certain parts of coal deposits.

The theory of the organic origin of *petroleum* seems to explain the existing association of petroleum with rock-salt, for it has been shown experimentally that the decay of animal, and perhaps also of plant, remains under a cover of salt water will produce petroleum-like substances.

Recent and Fossil Sediments.—The petrologic study of the characteristics of sediments, and a comparison of equivalent formations in different parts of the earth, have led to many surprising results. A characteristic of sediments now being formed in the tropics is their red color, due to the color of the weathered products. The processes of weathering, during earlier geologic periods, were undoubtedly the same as those operating at the present time, and the occurrence of red sandstones, red clays, and red calcareous shales is probably just as legitimate a proof of a former tropical climate as is the presence of coral reefs. Furthermore, extensive deposits of homogeneous, fossil-free sandstones indicate a former desert climate just as certainly as heterogeneous conglomerates of striated boulders indicate glaciation.

Thus a comparative petrographic examination of the facies of different formations shows not only the boundaries between the mainland and ocean basins of former geologic periods, but indicates the climatic conditions through which the earth has passed. While the mean climate of the earth has probably undergone no noteworthy change since the oldest fossil-bearing formations were deposited, the notable differences in the petrographic characters of the sediments seem to indicate that during geologic periods there have been geographic displacements in relation to climatic conditions, displacements such as may have been produced by a change in the position of the equator or by other astronomic phenomena.

Recent marine sediments generally differ from older deposits in being plastic instead of more or less consolidated, that is, the latter are better cemented. Occasional exceptions to this rule, such as the occurrence of sands and clays in the almost undisturbed Cambrian deposits of the Baltic Sea province, or of hard, transversely schistose slates in the Oligocene of the Glarner Alps, simply indicate that these differences are not diagenetic but that they originated some time after the deposition.

Pressure has been considered, apparently not incorrectly, the primary cause for the consolidation. In general, strongly-folded argillites with transverse cleavage are more consolidated than are those which have not been subjected to pressure. The fundamental cause for this is not definitely known; in the main it appears to be due to a decrease in porosity, as is the case when loose, artificial aggregates are compressed to coherent masses by great hydraulic pressure. At any rate, the character of the resulting alteration differs greatly from that produced by dynamometamorphism, for here there is no question of recrystallization or of other molecular re-arrangements. The rocks preserve their original clastic character, and even the colloidal, clay-like substances in very compact roofing-slates are unaltered.

The re-formation of the sedimentary rocks after the ending of true diagenetic processes has been too little studied to be conclusively treated at present. No definite conclusions can be drawn as to the active agents aside from than those that are of volcanic origin, nor are the processes themselves clearly understood.

VII. CONTACT-METAMORPHISM

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Agents of Contact-metamorphism. —Different magmas rising from the interior of the earth contain different amounts of dissolved gases and vapors. As was shown above, these gases act as mineralizers during the solidification of the rocks, and in many cases, with the gradual crystallization of the individual constituents, they accumulate in the concentrated mother-liquor.

When this also begins to solidify, the gaseous material is set free and produces certain stresses which may lead to explosions and the rupture of the overlying rock-complex. In other cases the cover is too thick and resistant, or the country-rock is so full of pores and other channels that the accumulated gases are forced into them, not only along fissures or schistosity-planes, but in such a manner that they thoroughly saturate the entire rock.

The mineralizers, now agents of contact-metamorphism, generally separate from the granitic magma only in the very latest stage of its solidification, that is during the crystallization of the quartz or of the eutectic quartz-feldspar mixture, and these agents, still very hot, saturate the rocks already heated by the igneous intrusion. While the dry heat of even the greatest in-

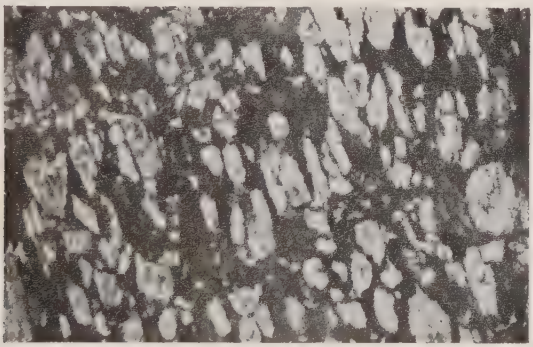

FIG. 71.—Greenstone-schist with porphyritic palimpsest texture. Harthau, near Chemnitz.

trusive masses can only penetrate to relatively slight distances into the country-rocks, owing to their low conductivity, the hot gases pervade them for long distances. This contact-metamorphism by magmas rich in mineralizers, may extend for many kilometers into the country-rock, especially if these have been greatly fractured by orogenic processes, as is seen in the schist zones around the central Alps. On the other hand, in the neighborhood of basic igneous rocks, such as gabbros or peridotites, which are poor in mineralizers, the contact-metamorphic effect disappears completely within 50 to 100 meters.

The mineralizing agents which passed from the intrusive mass into the country-rocks produced in them a mobility of molecules which usually led to re-arrangements, but although the neighboring rocks were saturated by the agents of contact-metamorphism and became soft, they did not become as mobile as igneous magmas. This viscosity is shown by innumerable phenomena. For example, in many cases the

earlier schistosity of sediments remains visible, in part megascopically, in part microscopically. This is especially well shown in the *helizitic* texture (Fig. 3, Pl. IV), in which many inclusions remain parallel to the former bedding but cut through the later contact-minerals. Coarser clastic constituents in most cases are attacked only around their peripheries, and still distinctly show their original forms. Furthermore, the finest structure of resistant fossils may be clearly recognizable in greatly altered rocks. The textures of porphyries and diabases, also, remain clearly visible in contact-metamorphosed greenstones which, but for this, would be indeterminable (Fig. 71). *Palimpsest texture* indicates that the constituents had but slight mobility during the crystallization of the contact-rock. In the so-called *sieve texture* (Fig. 1, Pl. IV), the larger crystals were formed in a viscous magma. While abundant inclusions are rare in the chief constituents of igneous rocks, contact-minerals may be so filled with them that the chemical composition can be determined with difficulty.

Contact-metamorphism, as a rule, does not alter the chemical composition of rock, even though it is completely metamorphosed. Simple molecular rearrangement, therefore, is the important

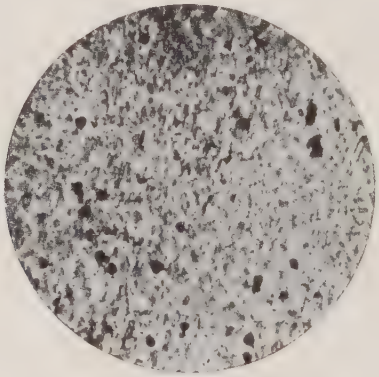

FIG. 72.—Tourmaline impregnation of a contact-rock. Bayumkol Valley, Tienschan.

factor. Chemical alterations, such as the loss of carbon dioxide by the formation of silicates in carbonate rocks, the loss or addition of water, and the introduction of fluorine, chlorine, boron, and other mineralizers, are of less importance. One of the most important changes in granite contact-rocks is the universal impregnation with tourmaline. This mineral may be megascopic in the inner zones, although ordinarily it impregnates the rock in small microlites. It is even present in argillites which are so little altered that there is only a suggestion of alteration of its clay-like material to mica, and in which the development of clay-slate needles has barely commenced. Fig. 72 is a photomicrograph of an altered schist containing innumerable, small, well-developed tourmalines. Tourmaline is especially valuable for the

recognition of contact-metamorphism on account of the ease with which it is determined. On the other hand, scapolite, which also is indicative of contact-metamorphism, is determinable with difficulty, and is therefore much more frequently overlooked. It is also very likely to be altered.

Feldspar, especially albite, may be secondary, as in certain *schistes feldspathisés*, the materials having been brought in by the mineralizers. But feldspathization by this means is doubtless much less common than is usually thought, since numerous argillites and similar rocks probably originally contained the constituents necessary for the formation of feldspar by molecular re-arrangement. Finally, many sulphide ores, hematite, etc., are secondary in contact-rocks.

The influence of the country-rocks upon soda-rich intrusives, such as nephelite-syenite, is in many cases very marked. For example, the lazurite content of lapis lazuli, an altered granular limestone at a nephelite-syenite contact, must be ascribed to mineralizers from the alkali-rich magma. Further, many components of the igneous magma are found in the contact-minerals, and fragments torn loose from the country-rocks are re-formed into sodium-, zirconium- and titanium-rich silicate aggregates.

Gases naturally diffuse much more slowly in compact country-rocks than in those that are more or less porous, yet under the influence of high pressure, extremely mobile, highly-heated gases are able to penetrate and re-form the densest rocks. Slow as this process is, it distributes the heat and prevents local fusion. Such rocks, therefore, as the plutonites, from which the mineralizers escaped gradually as the magma crystallized, generally do not melt the rocks with which they are in contact, but produce in them, to a considerable distance, a molecular re-arrangement and a general recrystallization. Where these mineralizers rapidly escape, however, as by the rising of extrusive magmas, a complete or partial melting (fritting) of the country-rock may occur, but this is confined to the part lying immediately adjacent to the igneous contact. All alterations of this character which preëxisting rocks undergo at the contact with igneous rocks are embraced under the term contact-metamorphism.

Contact-metamorphism Produced by Plutonic Rocks.—The contact-metamorphism produced primarily by mineralizers emanating from deep-seated rocks, varies greatly in intensity and extent, but *all processes of contact-metamorphism proceed in one direction, namely, to produce, for the given chemical and physical conditions, the greatest possible stability with the least alteration in the chemical constitution of the rock.*

It is not probable that all granitic magmas, at the time of their final consolidation, were equally saturated by gases, but in general the granitic magmas were richer in

them than were those which crystallized as gabbros or basalts. Only the degree of alteration produced in the country-rocks was influenced by these relationships, the kind of alteration was the same whether the rocks were basic or acidic. Enormous intrusive masses of granite or similar rocks naturally gave off great quantities of mineralizers during their slow solidification, and these eventually saturated and heated the country-rocks to great distances. Smaller masses gave off less gas, and the relatively rapid cooling soon ended the anamorphism.

With the exception of water, which is always predominant, the effect of the mineralizers from different magmas differed greatly. Traces of such agents still remain in the contact formations of many rocks, especially in those of the granite family. Thus the presence of boron- and fluorine-bearing tourmaline, topaz, fluorite and other fluorides, chlorine-bearing scapolite, etc., suggest the composition of the agents set free by the crystallization of the magma. At contacts of basic rocks, such occurrences are exceptional, scapolite being the mineral most commonly formed.

The extent and intensity of the alterations produced by contact-metamorphism do not depend solely upon the amount and nature of the metamorphosing agents but perhaps even to a greater degree upon the permeability of the country-rocks and the ease with which they can be recrystallized. As noted above, the metamorphic agents, being under high pressure, penetrate all rocks, no matter how intimately the constituents are intergrown, yet the distance to which the metamorphism extends depends largely upon the degree of consolidation or cementation.

Rocks, such as shales, argillaceous sandstones, and volcanic tuffs, whose coherence is relatively slight, and rocks which were originally compact but were subsequently greatly fractured by tectonic processes, are readily saturated to great distances. Very compact formations, on the other hand, such as fine-grained igneous rocks or siliceous sandstones, are much less permeable.

The bedding-planes of rocks offer easy passages for the mineralizers. Thin-bedded formations, therefore, are in many cases altered to great distances, the greater where the beds had become loose or porous by intense folding. Thin-bedded rocks, invaded by igneous stocks, are usually much shaken and faulted by the magma pressing forward, and these effects only gradually disappear far from the igneous body. As a result of the intrusion, the bedding planes were opened for the entrance of the gases, and saturation took place to surprising distances, especially if the intrusive material was forced between the beds in the form of apophyses.

Contact-metamorphism is not so great in thin-bedded rocks where the schistosity runs parallel to the contact, for example in the roof of a laccolith (cf. Fig. 5). The beds, raised by the magma, usually show many fissures across the stratification, and into these, parts of the magma are forced. The movement of the mineralizers, however, is generally along the bedding-planes, for there are but few passages at right angles to this direction, consequently the intensity as well as the extent of the contact-metamorphism is here very much less.

On the other hand, very extensive alterations occur in the above case if the roof scales off into the melt, or where a schist is torn apart by the intrusive mass and is injected with molten matter (cf. Fig. 36). The injected material, being usually the very mobile, mineralizer-rich mother-liquor, passes to great distances, and makes the contact-metamorphic alterations intense and extensive.

That the aplitic apophyses of granite are igneous may be clearly seen by the

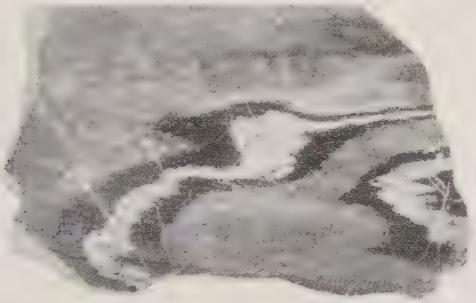

FIG. 73.—Hornfels showing increased metamorphism at the contact with aplite dikes. Riesenberg, near Ossegg, Erzgebirge.

additional alteration of the contact-metamorphosed rock directly at the margin of the dike. This is shown, in the andalusite-hornfels of Fig. 73, by a darker and much more distinctly crystalline zone exactly parallel to the aplitic apophysis.

Finally, the end-members of aplitic injections, namely, the granular quartz dikes which occur in the zone farthest from the main intrusion, are true igneous formations, as is shown by Fig. 74, which represents a knotenschiefer in which the cordierite

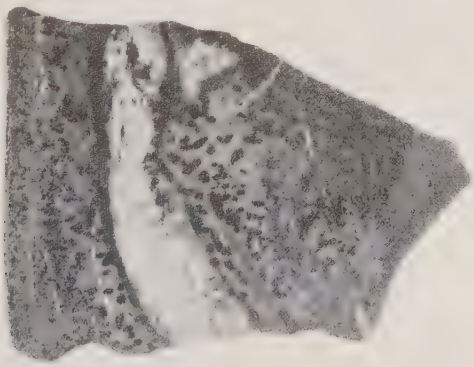

FIG. 74.—Knotenschiefer showing increased metamorphism at the contact with an igneous quartz dike. Plauen, Vogtland.

nodules have undergone a considerable enlargement at the contact with the injected pure quartz.

The susceptibility of a rock to alteration by contact-metamorphism is likewise an important factor. Rocks, such as certain sandstones, which are readily permeable by the mineralizers, are capable of very slight rebuilding; others which are well consolidated, such as certain basic igneous rocks or innumerable limestones, are readily altered.

Contact-metamorphism is hardly noticeable in rocks which are practically in a

condition of stable equilibrium for the given conditions; nor are rocks whose conditions of formation were nearly the same as those of contact-metamorphism much influenced by it. For example, no contact alteration appears where an older granite is intruded by a younger; but where a basic igneous rock is cut by a granite, distinct alterations appear, since the chemical and physical conditions under which the two were formed were different.

Sedimentary rocks are generally much altered at the contact, since the constituent minerals, brought together at random by the sedimentation, react upon each other to produce various minerals. The finer the individual components of the sediments, the more complete will be the mixing of the individual parts; consequently the recrystallization, which depends upon their reciprocal reactions, also will be more marked. Large fragments remain almost entirely unaltered so that the clastic character of coarse sandstones and conglomerates is generally distinctly preserved even after intense contact-metamorphism. Rocks predominantly of quartz are least altered, especially when the individual grains are of considerable size, as in sandstones. Here and there mineralizers pass through a whole complex of sandstones, poor in cement and therefore porous, without producing any externally visible alterations. It is true that even in these apparently unaltered formations, the beginning of recrystallization may be seen under the microscope, for the previously rounded quartz-grains are now interlocked, and the clay-like interstitial material is altered to a micaceous mineral. The clastic texture in these rocks appears much less distinct under the microscope than it does megascopically. Rocks of different character, however, lying beyond the limits of the sandstones, may be greatly altered by the metamorphic agents which passed through the latter without affecting them.

In certain exceptional cases, the metamorphism of the sediments has an anomalous character. For example, the calcareous country-rocks at the contact with the monzonite of the LeSelle Pass in the Monzoni valley are normally altered to silicate-rich, granular limestones for hundreds of meters. Locally, however, in the place of these extensive alterations, there occur narrow bands of siliceous hornfels of such density that they are irresolvable even under the microscope. In other regions, along limestone contacts, instead of the usual recrystallization products, there appear very siliceous dolomites which are ordinarily only a few meters wide and beyond which the sediments are practically unaltered. That these changes were not due to orogenic movements is shown by apophyses of the intrusive rock which penetrate the dense hornfels and dolomites.

Inclusions in plutonic rocks are usually more extensively metamorphosed than is the country-rock. Besides the resorption of basic inclusions by siliceous magmas, and acid inclusions by those that are silica-poor, both producing very unusual rock-modifications, there is also found an extensive injection and saturation of the inclusions by the magma. Here belong, for example, the so-called gneiss inclusions in granites, which are often cited as proof that gneiss occurs at great depths. They are, however, simply metamorphosed argillites which have been completely saturated with igneous material.

In later periods of volcanic activity the contact-minerals themselves may be replaced and altered, causing the contact-rocks to be filled with pseudomorphs and secondary minerals, such as serpentine, talc, kaolin, brucite, chlorite, sericite, etc.

In regard to names for contact-rocks, those here used are more or less accepted everywhere. No classification that is generally acceptible has been proposed, and the naming of each combination of secondary minerals would produce too complicated a nomenclature. But even the terms in use are not especially satisfactory. For example, the word hornfels generally carries with it the conception of compactness, yet all hornfels is not compact.

Contact-metamorphism of Argillites.—Most argillites consist of uniform mixtures of various very finely-divided constituents, and therefore, when metamorphosed, are likely to contain many kinds of secondary minerals. Since argillites are very permeable on account of their usual complete schistosity, the phenomena of contact-metamorphism are most beautifully and typically shown where these rocks are cut by igneous stocks. The development of altered zones at the contact between granite and argillites is so distinctive under normal conditions that contact-metamorphism was recognized here long ago.

Although the relationships may not be as simple as was formerly thought, and numerous modifications in the physical conditions

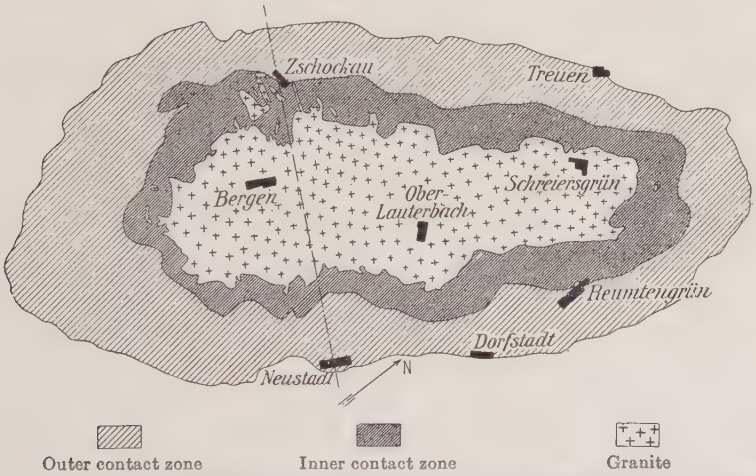

FIG. 75.—The Oberlauterbach granite stock with its contact-zones. Vogtland.

may make the meaning of the formative processes difficult to understand, yet normal contact-metamorphism of argillites, as the prototype of all contact-metamorphism, must be described in detail.

Naturally the sedimentary rocks lying nearest the igneous contact (Fig. 75) are most altered, and have undergone, in part, a complete internal re-arrangement. On this account the schistose structure is completely destroyed, and the original argillites are now hard, dark, hackly-fracturing hornfels, and form the so-called contact-breccias (Fig. 76). Under the microscope, the rock is completely crystalline and there is only a suggestion of the original schistosity in the helizitic texture. Isolated fragments of argillites,

torn loose at the contact, are especially greatly altered, and are penetrated by veins of the igneous rock.

Farther from the contact, the haphazard texture gradually gives place to one that is distinctly schistose though still holocrystalline. Certain minerals, also, develop as phenocrysts, usually with very poor boundaries, and the rock takes on a porphyritic appearance. Such rocks are called *Knotenschiefer*. Still farther from the contact the crystalline appearance, megascopically as well as microscopically, gradually decreases, and through all possible transitions normal argillites appear in the outer contact-zone. However unaltered the latter rocks may appear to the

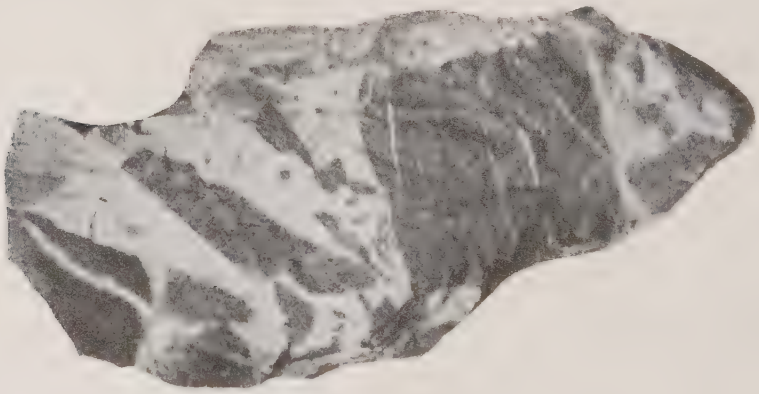

FIG. 76.—Contact-breccia. Geyer, Erzgebirge.

unaided eye, under the microscope they may still show, for a considerable distance, the gradually decreasing effect of the contact-metamorphism.

As already mentioned, rocks of different compositions are susceptible to metamorphism by the agents of contact-metamorphism to very different degree. Thus while the different members of the great Paleozoic slate series appear alike externally, in many cases there is actually a great variation in composition from bed to bed. Just as kaolin beds may be interbedded between strata which were originally normal weathered material, for example in the Carboniferous of Ruhr and the Rheinpfalz, so also may there be extensive changes in the character of the altered rocks in one and the same zone. Hornfels has been considered to be the exclusive rock of the inner contact-zone, probably primarily because contact action was first studied in heavily-timbered mountain regions of moderate elevation. Here the compact hornfels stands out prominently after the more schistose material lying between has weathered out, and the residual boulders usually consist of the same resistant rock.

Where deep cuts have been made in such contact-zones, however, the different stages of alteration of the alternating beds are found directly at the granite contact. This line, however, is not simple, but complicated by innumerable apophyses and by

the effects of numerous replacement processes. Fig. 77 shows a contact between granite and various schists and argillites.

The minerals of the dense hornfels (Fr. *cornéennes*) are very numerous. Quartz is probably never absent from the rock, and

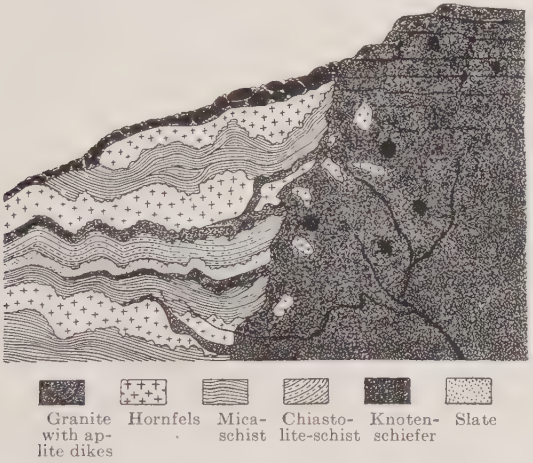

FIG. 77.—Contact of granite with various schists.

it may be of considerable importance. Next in importance are the aluminium silicates andalusite and sillimanite, then cordierite. Further, almandite and staurolite, both usually megascopically

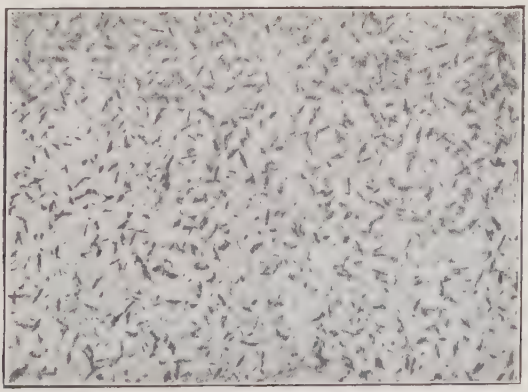

FIG. 78.—Knotenschiefer. Tirpersdorf, near Ölsnitz, Vogtland.

visible, micas and chlorite, spinel, feldspars, especially albite and more rarely orthoclase and microcline, and finally prehnite, lawsonite, the epidotes, and corundum occur. The ores are ordinarily present, ilmenite as an original constituent, and hematite, pyrite,

and magnetite secondary. The organic material originally in the schist is altered to finely-distributed graphite, which may literally fill the other contact-minerals as inclusions, and, with the micas, mark the helizitic texture of the rocks. Tourmaline is probably never wanting microscopically, while scapolite may be seen megascopically in many light-colored spots rich in inclusions.

True hornfels entirely disappears at a distance of rarely more than a few hundred meters from the contact, and the country-rock becomes more and more schistose,

FIG. 79.—Garbenschiefer. Zemmgrund, Zillertal. (1/4 nat. size.)

forming *Hornschiefer*, and this, in turn, by the increasing predominance of the micas, takes on an appearance similar to mica-schist. Darker spots, richer in graphitic material and usually representing poorly-developed and inclusion-rich crystals of the silicates, occur indistinctly upon the schistosity-planes of *Fleckschiefer*. In *Knotenglimmerschiefer* and *Knotenschiefer* the spots are more distinct. The last two are also called *Fruchtschiefer* (Fig. 78), probably on account of the fruit-like appearance of the knots. The minerals of these knots are rarely determinable megascopically, although in chiastolite-schist the peculiar distribution of the inclusions may indicate andalusite. Even under the microscope they cannot always be determined; they usually consist of andalusite and cordierite. Similar to Knotenschiefer are *Garbenschiefer* (Ger. *Garben*, sheaf, Fig. 79) which are characterized by sheaf-like aggregates of hornblende upon cleavage surfaces.

FIG. 80. —Profile through Fig. 75.

The knots and the luster of the schistosity surfaces do not die out, in many cases, until a distance of several kilometers has been reached, and the rocks pass first in external habit, then internally, into normal, unaltered argillites. Not until this original condition appears do the small tourmalines, which are characteristic of contact-metamorphosed rocks to their farthest outliers, disappear.

The limits of the different contact-zones are rather irregular. They do not form concentric shells around the igneous body but are developed to a greater or less extent in different places. Certain members may be wholly wanting on one side, while on another they may be most extensively developed. The contact-zone may appear

much wider at the surface than it actually is, as is shown by Fig. 80, which is a cross-section through Fig. 75 along the line indicated. On account of the gentle slope of the contact of the granite with the schist at the left of the diagram, the igneous mass is actually much nearer the surface than it appears to be from the outcrops.

Contact-metamorphism of Carbonate-rocks. — Finely laminated, schistose rocks and those which were much fractured in the contact-zone, permit the mineralizers to penetrate to great distances. The more thickly-bedded and consolidated carbonate-rocks are very much less permeable, yet they show themselves especially sensitive to metamorphism, and recrystallized fragments of these rocks may be found embedded in very slightly altered schists of the first group.

This difference appears very distinctly in the inner contact-zone. Here the carbonate-rocks have taken on a coarse-granular texture in contrast to the usual dense hornfels. Recrystallized limestones and dolomites appear quite different under the same conditions, the latter being usually much finer grained than the former, which, when pure, may consist of individuals an inch in length directly at the contact. Such coarse-grained dolomites are rare, however.

The organic inclusions in the original rock have an important influence upon the size of grain of the metamorphosed carbonate-rocks. They alter to finely divided graphite, and when this is uniformly distributed through the altered rock, a decided diminution is produced in the size of grain. Thus the gray to black bands in carbonate-rocks are always much finer grained than the white.

Normal contact-metamorphism by plutonic rocks produces no essential alteration in the chemical composition of carbonate-rocks. Although small amounts of tourmaline, fluorite, or scapolite, or even of secondary quartz or albite, occur in limestones thus altered, on the whole the addition of foreign constituents is just as rare here as it is in normal contact-metamorphism of other rocks. Pure limestones, therefore, are usually altered to pure white marbles. In argillites the different substances which lie in contact with each other usually react under the influence of mineralizers to produce new minerals. Such contact-minerals do not appear in pure, dense limestones, for these rocks, before metamorphism, consisted of a fine, crystalline aggregate of calcite which originated by diagenesis, and their alteration is shown

primarily by an enlargement of grain which transforms their megascopically dense structure into the distinctly crystalline texture of marble.

Ordinarily, however, compact limestones are not pure, but contain a greater or lesser amount of clastic aluminium silicates which, under increased temperature and with the assistance of mineralizers, react in various ways with the calcium and magnesium carbonates. Normally, the carbon dioxide is driven off, and the original impurities may form large crystals of calcium-aluminium silicates such as garnets, vesuvianite, epidote, anorthite, and mica—especially phlogopite. They also form calcium-magnesium silicates such as the pyriboles, magnesium silicates such as forsterite and minerals of the humite group, and rarely the pure calcium silicate wollastonite. Entirely absent, however, in these

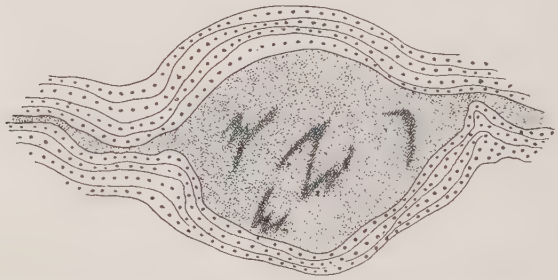

FIG. 81.—Marble lens in gneiss, formed by the squeezing-together of a thin bed. Steinhag, near Passau.

recrystallized limestones or *calciphyres*, are the typical minerals of the argillaceous hornfels, above all aluminium silicates such as almandite and staurolite. Furthermore, cordierite is wanting, but spinels or even corundum may occur.

The slight mobility of the substance of the rock during metamorphism is also clearly shown here. The original schistosity is distinctly preserved in many cases, especially in folded and schistose mica-cipolins, and the fossil remnants of echinoderms, corals, belemnites, etc., are here and there easily recognizable, and show clearly that these marbles are not primordial. The larger contact-minerals of the calciphyres are as rich in inclusions as are the knots in knotenschiefer, and their rounded edges and pitted surfaces give them the appearance of having been partially fused. While the mineralizer-saturated limestones were but slightly mobile, on the whole they were very plastic, as is shown by

the adaptability of their forms to their less plastic enclosures. These properties show why inclusions of silicate rocks in many granular limestones are broken into fragments, yet are everywhere surrounded by aggregates of carbonates which show no traces of cataclastic structure, or why thin layers of limestone within silicate rocks are squeezed together into thick lenses, like the common inclusions of so-called "primeval" limestone in schists (Fig. 81).

The contact-metamorphism of limestones is not nearly so well understood as is the normal contact-metamorphism of argillites. This is so, primarily, because so many anomalous phenomena occur at granite-limestone contacts. It is not uncommon to find peculiar formations between the two rocks, such as the silicified hornfels of Monzoni, or the compact silica-rich dolomite described on page 122. Likewise, the constituents of the magma in many cases mix with those of the limestone, and lead to numerous, peculiar, silicate aggregates. Finally, at the contact, there may be broad zones of wollastonite or of compact calcium-aluminium or calcium-magnesium silicates. These aggregates may extend far into the marble, in part in the form of dikes, in part as very irregular patches. In the latter, calcium carbonate has unquestionably been replaced by material derived from juvenile solutions.

FIG. 82.—Garnet dike (dark) with wollastonite selvedge in marble. Auerbach along the Bergstrasse.

The granite itself may show endogenic modifications at the contact with the marble, and there may be within it a rather broad zone of garnet, epidote, vesuvianite, wollastonite, pyroxene, or other minerals which usually occur in isolated crystals in contact-metamorphosed limestone. Geologists have usually regarded these minerals, which are doubtless entirely anomalous, as the normal products of contact-metamorphism of limestone, and when such minerals are not present they have thought the normal contact-metamorphism due to other factors, especially dynamometamorphism. That this conception is erroneous, and that these minerals are not necessarily due to contact-metamorphism is shown by the occurrence of dikes of these silicates in granular limestones. For example, the small veins of dark garnet which cut the wollastonite in Fig. 82 clearly show the secondary character of the entire formation. Small masses of such silicate aggregates may occur in the limestone, and may carry, here and there, iron sulphides and oxides. In places these deposits, which show all transitional phases to marble, may be of such extent that they are valuable for the iron they contain. When coarse grained they are called *skarn*.

Normal contact-minerals of limestones are iron-poor grossularite and clinozoisite, and light-colored diopside and tremolite, while the silicates of the dike-aggregates are relatively high in iron. The silicate and oxide manganese ores of many granular limestones have skarn-mantles rich in manganese-bearing silicates, while the skarn of the zinc-manganese deposits of Franklin Furnace, New Jersey, contains an abundance

of abnormal zinc-manganese silicates. Since these minerals are abnormal in contact-metamorphosed limestones, they could only have been brought in by juvenile waters. The same is true of masses of siderite and magnesite which occur similarly in contact-metamorphosed carbonate-rocks.

While limestones are easily altered by various chemical agents, they do not always change so far as to be unrecognizable. Marbles are the normal contact-rocks of pure limestones, and calciphyres and cipolins of those that are impure. The calciphyres contain large phenocrysts or aggregates of silicates, spinel, corundum, tourmaline, fluorite, scapolite, and blue apatite; the cipolins are schistose rocks rich in mica and chlorite. With the exception of tremolite and wollastonite, which almost exclusively occur in ray-like, leafy aggregates, the contact-minerals have distinct but incomplete crystal outlines, and may be of considerable size. Ordinarily they are very full of inclusions.

The more impure the originally dense limestone, the greater the amount of newly formed silicates. In the alteration product of calcareous marl, calcite is almost or entirely gone, and the rock now consists predominantly of xenomorphic-granular aggregates of calcium-aluminium and calcium-magnesium silicates. These minerals usually differ from those of the skarns in their small content of the heavy metals, as was to have been expected from the composition of the original clastic constituents of the dense limestone, derived as they were from iron-poor weathered residues.

Organic substances are universally distributed through sedimentary limestones, and they may be altered by contact-metamorphism to graphite, as in argillaceous hornfels. This mineral occurs in granular limestones in three forms; first, as fine, evenly distributed dust through the rock, producing the gray to black color of marble; second, in small, scaly nodules, and, finally, in well-developed crystal-plates which may be over a centimeter in diameter. The first variety probably came in most cases from original organic material in the limestone; the second, however, which is ordinarily associated with dust-like graphite and occurs in fissures and along planes of movement of the rock, is probably a product of fumarolic action. The third variety, which is almost always associated with rich graphite deposits, has probably the same mode of origin as the second. All of the original organic constituents of the limestone, however, are not altered to graphite by contact-metamorphism; the malodorous, skatole-like constituent of stink-stone, which is especially resistant, is in many cases, even in coarse-grained marbles, preserved entirely unaltered except directly at the contact. Where the evil odor disappears delicate blue, rose-red, or lemon-yellow tones, which fade readily upon exposure to light, are developed. These beautiful, coarse-grained marbles represent the stage of greatest alteration. Within a few meters they are again light grey in color and malodorous when struck.

Among the sedimentary carbonate-rocks, dolomitic limestone and dolomite are of some importance. The weathered surfaces of many limestones which have been altered by contact-metamorphism show a rough surface or sandy coating of normal dolomite. Microscopic examination of the fresh rock shows clear grains of dolomite among cloudy grains of calcite. The double salt dolomite and the simple calcium carbonate, therefore, crystallized out independently. In other marble-like rocks, such as predazzite and penkatite from Predazzo, octahedrons of periclase or pseudomorphs of brucite after periclase occur in the main mass of granular limestone. Here the more easily calcined magnesium carbonate may have lost its carbon dioxide by heat.

Pure, granular, dolomite contact-rocks are widely distributed. In texture they are usually not very coarse, and they are always finer grained than the adjacent limestone. In general, they are rather friable on account of the tendency of the dolomite to crystallize, and many of them, therefore, are decomposed to sandy, so-called "dolo-

mite-ash." Many kinds of contact-minerals, such as tremolite, the magnesium silicates forsterite and humite, and rarely spinel and corundum, are found in granular dolomites.

The numerous minerals of the saccharoidal dolomite of Binnental, including sulphides and sulphosalts as well as tourmaline, are probably due to hot juvenile springs. It cannot be determined with certainty whether these and other contact-dolomites originated from dolomitic sediments or from limestones to which magnesia was added, during the process of recrystallization, by the action of the agents of contact-metamorphism.

Finally, the alteration of other sedimentary rocks by deep-seated contact action may be briefly mentioned here. The mineralizers consist predominantly of superheated water which simply dissolves the different salts. Contact-minerals are found, here and there, in gypsum and anhydrite; for example, phlogopite occurs with tourmaline in these rocks in St. Gotthard, and with scapolite in the Pyrenees.

When coal is altered by contact-metamorphism, dense graphite is formed, but the structure of the coal may still be clearly recognized in many cases. The final state of normally altered coal is carbon-rich anthracite, which crackles or even explodes upon heating on account of the large amount of gas included.

Contact-metamorphism of Basic Igneous Rocks.—The magmas from which basic igneous rocks are derived are usually poor in mineralizers. These rocks therefore almost entirely lack the hydroxyl-bearing minerals of the mica and amphibole groups, but in their place occurs pyroxene. Where such rocks have been metamorphosed by contact with alkali-rich rocks, they are, in many cases, completely recrystallized by the mineralizers emanating from the latter. Analogous alterations occur in the great tuff deposits which accompany basic extrusives, and it may be difficult to determine the original character of rocks which have been completely altered by contact-metamorphism.

FIG. 83.—Greenstone-schist (metamorphosed labradorite-porphyrite) with phenocrysts showing good boundaries.

Volcanic tuffs may be interbedded with various sediments. When typically metamorphosed basic igneous rocks, such as eclogites, amphibolites, or greenstone-schists, are connected by transition members with interbedded marbles or knoten- or mica-schists, it is quite certain that at least a part of the series was originally formed by tuffs. Palimpsest texture, that is, one in which remnants of a former texture are recognizable, may suggest something as to the original character of the altered rock. Heli-

zitic textures indicate originally schistose tuffs, while distinctly recognizable ophitic or porphyritic textures (Fig. 83) suggest massive igneous rocks.

Of all rocks, basic igneous rocks and their tuffs are most sensitive to the agencies of contact-metamorphism, and in many cases they may be found in a greatly altered condition interbedded between argillites which show but slight traces of alteration. These feldspar-bearing, basic, igneous rocks, such as gabbro, labradorite-porphyrite, trap, and melaphyre, are characterized by a rather low percentage of silica and soda, and a considerable amount of the oxides of the bivalent metals and titanium. The chief mineral constituents are a soda-poor aluminium-rich plagioclase, a soda-free aluminium-poor augite, and some ilmenite.

Where most completely altered, these rocks pass into eclogites, which, in their purest varieties, consist of the light-green, soda-bearing pyroxene, omphacite, and an alumina-lime-iron garnet, near almandite in composition. Titanium oxide occurs in the form of microscopic individuals of rutile. Soda-bearing hornblende, which marks the transition to the glaucophane rocks, is of primary importance among the innumerable accessories. The complete absence of feldspar is noteworthy, the soda content having passed into the pyroxenes and amphiboles. Every trace of the original texture of the rocks has disappeared in the intense molecular rearrangement of the constituents.

In most cases, however, the alteration is not so great, even directly at the contact, and amphibolites are formed. In these rocks the saussuritized plagioclase and the uralitized pyroxene are usually still distinctly separated, one from the other. Saussurite is composed of a dense aggregate of the calcium-aluminium silicates clinozoisite and lime garnet, and finely divided acid-plagioclase, usually albite. Uralite is ordinarily common green hornblende. In many cases it still shows, under the microscope, uniformly distributed brown rods, indicating its origin from diallage. Titanium oxide occurs not only in the form of rutile but as titanite and leucoxene, and ilmenite is also found. All possible transitions exist between eclogite and amphibolite, the most common intermediate rock being garnet-amphibolite.

Remnants of original textures in amphibolites may be distinctly recognized megascopically, but microscopically they are less clear. Many amphibolites are coarsely crystalline, but with increasing distance from the granite contact-zone they usually become finer grained and take on a distinct schistosity. The saussuritized plagioclase phenocrysts of the original porphyrite may appear quite prominent megascopically, otherwise the rocks are uniform, compact, green schists, whose mineralogic composition is only recognizable under the microscope. When they have a considerable content of chlorite they are called *chlorite-schists.*

Serpentinization of Feldspar-free Rocks by Contact-metamorphism.—Finally to be considered are the feldspar-free igneous rocks, among which peridotites are the most widely distributed. The great majority of these rocks are serpentinized. They generally occur in compact, lens-like masses concordantly interbedded

with the schists that form the different contact-zones of the granite. Some gneissoid granites contain small, rounded masses of serpentine with invariable rims of chlorite scales. Within this shell, which allows them to drop out of the granite quite readily, there is usually a zone of radial needles of fibrous hornblende. This zone stands out in sharp contrast to the inclusion itself, which is compact and is composed of serpentine with talc and chlorite.

If these inclusions are compared with the border-zones of certain central Alpine serpentines whose contacts are well disclosed, it will be found that they are generally analogous (Fig. 84). The outer zone of such a serpentine mass is formed of coarse scales of

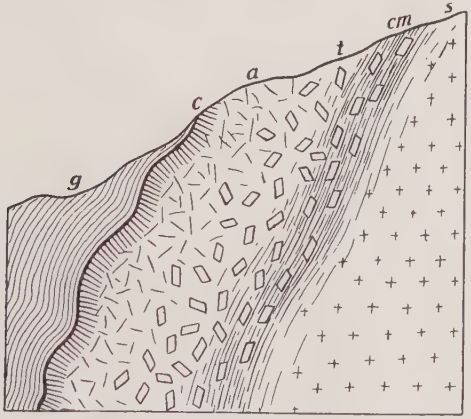

FIG. 84.—Contact of serpentine, Greiner, Zillertal. *g*, Gneiss; *c*, coarse chlorite; *a*, talc with actinolite; *t*, talc with magnesite; *cm*, chlorite rock with magnesite; *s*, serpentine.

chlorite surrounding a band of actinolite standing normal to the contact. Within this is a transition-zone of talc and chlorite, and finally comes the compact serpentine. The conclusion appears justified that these two corresponding modes of occurrence have the same geologic significance, namely, both are due to mineralizers from granite acting upon peridotite. They represent, therefore, true contact-zones, the peridotite being the older rock and the granite the younger.

This age relationship is further shown by the fact that fresh normal peridotites never carry rich ore deposits; the mineral-veins ordinarily associated with serpentines being entirely wanting. In the central Alps the veins cutting the serpentine usually carry minerals which were entirely foreign to the original peridotites, and which bear no chemical relationship to them. Normal peridotites are free from titanium and

zirconium; in the central Alpine serpentines, ilmenite, titanite, and perofskite are not uncommon, and zircon occurs locally in large crystals. In the contact-formations of all basic rocks, and especially of peridotites, fluorine- and boron-bearing minerals are usually entirely wanting, but in the dikes in the central Alpine serpentines tourmaline is not rare, and in many cases it occurs in large crystals. These phenomena show a consanguinity between the dikes in the serpentine and the Alpine Titan-formation, the latter belonging to the post-volcanic period of the central granite, and prove that the serpentine is older than the granite.

Contrasting with the innumerable serpentine masses of the central Alps in which remnants of original olivine are only rarely preserved, are the numerous occurrences of fresh peridotites in the Pyrenees where the alteration to serpentine is exceptional. Here, however, these feldspar-free igneous rocks are clearly younger than the granite.

These observations, therefore, seem to indicate that the formation of serpentine depends upon emanations from a younger granite, or that it represents the normal contact-metamorphism of peridotite. While most massive serpentines are probably best explained on this hypothesis, there is no doubt that olivine may be changed to serpentine by the action of water, probably exclusively juvenile. That this is the case is clearly shown by the serpentinized olivine in many gabbros, melaphyres, and basalts; but it may be definitely asserted that this serpentinization was not produced by atmospheric agents.

Piezo-contact-metamorphism.—If the phenomena of contact-metamorphism be observed in regions where orogenic processes accompanied the solidification of the igneous rock, innumerable modifications will be noticed, for the piezocrystallization of the igneous rock is accompanied by piezo-contact-metamorphism of the country-rocks. The latter, already fractured by the intrusion, were generally still more shattered and fragmented by the process of mountain-folding. This shattered condition and the great pressure caused the mineralizers to enter far into the rocks and made the contact-metamorphism here of much greater intensity and extent.

The effects of the metamorphism upon the different constituents varied with the physical conditions. The chief constituents of the recrystallized rocks show the effect of high pressure by their greater specific gravities, their occasional higher hydroxyl content, or their widespread condition of schistosity. In common with normal contact-rocks they constantly carry tourmaline. Furthermore, characteristic textural forms, described in greater detail in Part X, are especially well developed. Garbenschiefer and knotenschiefer are nowhere more characteristically developed, nor of more widespread occurrence than in the schistose border-zone of the central Alpine granite. The changes produced depended primarily upon the mineralogic composition. The action of the law of volumes, that is the tendency under given conditions

for a body to occupy the smallest possible molecular volume, is clearly shown.

In few regions are granitic intrusives so extensively mingled with the surrounding rocks as in the gneiss-mica-schist zone of the central Alps. Here true *mixed* or *hybrid* rocks, called *migmatites* (Gr. μῖγμα, a mixture), are extensively developed. Apophyses of the granite extend far from the intruded mass, and aplites and coarse-grained pegmatites are encountered many kilometers away. Dikes and beds of quartz, in many cases tourmaline-bearing, are very abundant in the zone of the less crystalline quartz-phyllite far from the igneous mass. These younger intrusives readily take up carbonates, especially ankerite $(Ca,Mg,Fe,Mn)CO_3$, and the most distant phyllite zone is full of massive quartz-ankerite dikes, in many cases coarse in texture.

A great mass of evidence having shown conclusively that the crystalline border-zone of the central Alps is not of Archean age, it became the chief region for demonstrating the theory of dynamometamorphism. The volume-law mentioned above, and the wide distribution of schistose structures in the border-zone were given as special proofs of dynamic recrystallization. There is good reason to believe, however, that the schistose shell is of piezo-contact-metamorphic origin, the principal evidence being as follows:

The innumerable mechanically formed textures (cf. Part X) shown almost everywhere by the granite, and the schistose character of the border in many parts, led to the correct conclusion that these were the results of orogenic forces, but these features were incorrectly supposed to have been impressed upon the rocks long geologic periods after they had been completely solidified. Even the name *protogine* (Gr. πρῶτος, first, γίγνομαι, to be born), which was applied to these rocks, indicated the belief in their consolidation as a part of the original crust of the earth, or at least in their great age as compared with the known younger, overlying, crystalline schist.

On petrographic examination, the schistose border everywhere shows distinct and indisputable evidence of contact-metamorphism. The injection schists and the true hybrid-rocks of the gneiss-mica-schist zone prove not only that these are older deposits, but that the granite itself is a later intrusion into this shell of former sediments and basic igneous rocks. The same age relationship between the two rock-groups is shown by extensively developed pegmatites, ramifying aplites, and quartz-dikes. At the contact of the latter with the schists, an increase in metamorphism is, in many cases, just as distinctly recognizable as it is near the igneous quartz-dikes of normal knotenschiefer. Furthermore, the mosaic, sieve, helizitic, and other textures characteristic of contact action, are especially well developed in the country-rocks of the central Alpine granite, and impregnations of tourmaline extend far out into rocks otherwise practically unaltered.

Here as elsewhere in contact-metamorphosed regions, the metamorphism is more intense the nearer the rock lies to the granitic intrusion. Finally, it is to be especially emphasized that mechanical textures, which were regarded originally as essential to dynamometamorphism, are entirely wanting in the altered schists of great portions of the central Alpine region. Likewise the aplites, which represent the final extrusions of the granitic magma, show no cataclastic structure, and many pegmatites

contain large, open druses which could not occur if these rocks were contemporaneous with the orogenic movements.

Thus there is strong proof that the crystalline schists of the central zone of the Alps were formed by contact-metamorphism. It is true that this metamorphism must have taken place under anomalous conditions, but the mineral composition of the central granite itself points to like anomalous relationships, namely, of especially high pressures during the solidification of the magma.

Andalusite and cordierite, the commonest minerals of normal slate-hornfels, are entirely wanting among the essential constituents of the Alpine schist-zone. They occur here only as constituents of pegmatites whose marked drusy character definitely shows that pressure had ceased when they solidified. Instead of these minerals, piezo-crystallization produced micas, especially the heavier brittle micas, and garnet, zoisite, and staurolite, the last three frequently leading to the formation of knotenschiefer. Disthene in sheaf-like aggregates on schistosity-planes also occurs. Where mica predominates, very schistose rocks take the place of hornfels; mica-schist, therefore, is the usual rock.

The modifications produced by the metamorphism of carbonate-rocks are entirely analogous. Under the existing high pressures, the carbon dioxide of the calcite was not replaced by silica, and quartz, in rounded crystals similar to those found in quartz-porphyries, is here a widely distributed constituent. Calcium-aluminium silicates are rare. Magnesium silicates are only developed in exceptional cases, but in their place occur albite and the micas, and in very impure rocks abundant epidote also. Amphibole is almost the only calcium-magnesium silicate present. The schistose structure is distinct in the more impure varieties of this group, the type-rock being a calcareous mica-schist. The purer varieties of calcareous rocks, under similar conditions, developed a compact texture, as in marble.

Paragenesis of Contact-rocks.—Various combinations of the chief minerals of contact-rocks have produced a great variety of forms.

1. Characteristic of slate-hornfels are: Corundum, spinel, andalusite, sillimanite, staurolite, cordiertite, mica, chlorite, almandite, hornblende, zoisite-epidote, rutile, anatase, ilmenite, graphite, quartz, and various feldspars. Under high pressure, disthene, brittle mica, etc., take the place of andalusite, sillimanite, and cordierite.

2. Characteristic of contact-limestones and calcium-silicate rocks are: Calcite, dolomite, periclase, spinel, grossularite, vesuvanite, gehlenite, zoisite-epidote, anorthite, diopside, fassaite, phlogopite, actinolite, pargasite, forsterite, humite, wollastonite, titanite, and graphite.

3. Characteristic of saussurite- and diabase-hornfels are: Zoisite, epidote, vesuvianite, lawsonite, prehnite, grossularite, albite, fassaite, glaucophane, wulfenite, chlorite, common garnet, disthene, and rutile.

To each of these groups may be added some of the minerals developed by the action of mineralizers. Among these are tourma-

line, topaz, fluorite, scapolite, apatite, pyrrhotite, pyrite, magnetite, etc. Finally, the replacement products of contact-minerals, which will be spoken of later, may also occur.

In conclusion, a few of the laws of association which seem to hold for contact-metamorphism may be given.

1. Andalusite, sillimanite, disthene, staurolite, cordierite, and the brittle micas are wanting in calcite-bearing contact-rocks.

2. Grossularite, clinozoisite, gehlenite, and vesuvianite are met with only in lime-rich rocks.

3. Forsterite and the humites are formed in granular limestones only when no alumina remains, otherwise calcium-magnesium silicates and spinel are developed.

4. Wollastonite forms only in rocks which are very rich in lime, and even here it only occurs when no foreign substances except silica are present.

5. Calcium-magnesium silicates occur also in rocks very rich in aluminium.

6. Rutile is especially abundant in rocks which are rich in aluminium, and then it occurs in association with the minerals mentioned under (1). It is rarer in calcium-aluminium silicate rocks.

Contact-metamorphism by Extrusive Rocks.—The character of the contact-metamorphism by extrusive rocks is somewhat different. Here the action of heat is the most apparent effect, for some of the rock-constituents are melted and the altered rock appears half glassy. Rocks partially melted in this manner are spoken of as *fritted*, and there are, for example, fritted sandstones in which the cement is melted, and fritted granite with its mica and a part of its feldspar altered to glass. Other changes produced by contact-heat are the alteration of coal to coke, and the production of prismatic parting in all kinds of rocks.

In the re-fused portions of fritted rocks, microscopic examinations show that minute new minerals have been formed. In some cases these may be determinable as cordierite, sillimanite, or spinel, but usually they are so small that they appear only as crystallites. It is only at the contact of extrusive rocks with limestones that a re-formation, analogous to that at the contact of plutonic rocks, is ever to be observed, and even here it appears only in very narrow zones. Granular marbles may here and there be developed in this manner.

Accompanying the partial melting there also occurs, in many cases, a silicification of the rock, as in porcelain-jasper (*porcellanite*). The occurrence of silicified wood at many points of contact with extrusive rocks is also noteworthy, and *adinole*, which is found at many diabase-contacts, should also be considered here. The most striking change in the alteration of the original argillite to adinole is the increase of as much as 10 per cent. in the soda content. Chemically, therefore, there is here a certain analogy with albite-gneiss, the greater part of whose albite was brought in, subsequent to deposition, by the agents of contact-metamorphism. Adinoles as well

as porcellanites are dense, hornfels-like rocks. The former are usually mottled and grey in color, the latter violet or reddish brown. With increasing distance from the diabase-contact, they grade through *desmosites* and *spilosites*, which represent less altered and more schistose formations, into normal argillites. Another rock which occurs at diabase-contacts is siliceous schist or *lydite*, a black, dense, splintery fracturing, greatly silicified rock with hardly noticeable schistose structure. All of these forms of alteration have a similarity to the anomalous alterations in deep-seated rocks noted on page 122.

The molten magma, forcing its way to the surface, may bring up many solid fragments. These may be hurled out in the form of bombs and lapilli and appear in the volcanic tuffs, or they may occur as inclusions in the solidified lava. Some of the inclusions and ejectamenta originated during the differentiation by slow cooling of the magma itself while it was still within the depths of the earth. Such primary differentiation products are especially abundant in lamprophyres and basalts, and are probably never wanting in them. They also occur in other extrusive rocks, generally in the form of granular masses, such as those of sanidinite in trachytes, etc. Other fragments are portions of the country-rock which were torn loose in the depths of the earth by the magma during the earliest stages of its solidification. Here belong gneiss inclusions in plutonic rocks and certain fragments enclosed in the older lavas of Vesuvius. The latter were thoroughly saturated by the magma and its mineralizers, and are extremely rich in pneumatolytic minerals. The composition of the alkali-rich lava in which they are enclosed had a marked influence upon their constituents, so that, like the sanidinites, they ordinarily contain alkali-rich silicates.

Rock-fragments, on the other hand, torn from the conduit-walls by the volcanic magma on its way to the surface, and therefore representing inclusions more recent than those just described, show especially the action of heat. Among such rocks are fritted granites and sandstones, in many cases with rod-like partings, and baked clays. Many such inclusions are assimilated and resorbed, and now appear in the form of glass lumps in rocks otherwise distinctly crystalline. Lamprophyres not uncommonly contain rounded and porous orthoclase crystals, or quartz-eyes. The former are the so-called chagrined feldspars, and seem to have been corroded by the magma, the latter are rounded grains with glassy rims filled with radial needles of augite or hornblende.

VIII. POST-VOLCANIC PROCESSES

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Post-volcanic Phenomena.—Succeeding the true volcanic action, that is, the extrusion of molten material, came various chemical changes, some of them very intense, which may be considered together under the name of post-volcanic processes. The first changes following the eruption were caused primarily by hot gases and vapors, and are therefore called *pneumatolitic* (Gr. πνεῦμα, vapor, λύειν, to set free). In a second phase, representing a stage of decreased volcanic energy, the changes were produced by superheated solutions. This *pneumatohydatogenic* (Gr. ὕδορ, water) period generally passed into the *thermal* (Gr. θερμός, hot) stage of hot springs. Geologically, these three post-

volcanic processes represent stages of decreasing activity, which have passed with such extreme slowness that they have endured through whole geologic periods. The principal gases and vapors brought up by the so-called fumaroles are compounds of sulphur, boric acid, hydrochloric acid, hydrofluoric acid, and carbon dioxide. Hot springs contain the same agents, usually in combination with alkalies and alkaline earths, and many also carry silicic acid, various heavy metals, etc.

When post-volcanic action occurs, it is intimately connected in time with contact-metamorphism, but its effect upon the chemical composition of the rocks is usually much more marked than is that of the contact action. It not only alters the metamorphosed rocks adjacent to the volcanic masses which it accompanies, but in many cases produces a great change in the igneous rocks themselves. Post-volcanic phenomena are closely related in time to volcanic action, and always occur near the igneous contact, the most intense action being nearest the contact. The processes by which these agents produce changes in a rock are called *replacement* processes. Contrasted with weathering, which is regional, replacement is of purely local significance.

Post-volcanic processes may form new minerals, or metamorphose those already present, or destroy them entirely. On the one hand they produce most of the new minerals occurring in mineral- or ore-veins, on the other they change the character of the rock itself. The latter change may be a simple molecular re-arrangement such as occurs in saussuritization, and therefore analogous to contact-metamorphism; or it may be a chemical alteration produced by the leaching of some of the constituents as in kaolinization, by the addition of material as in tourmalinization, or by an interchange of certain components as in the formation of talc.

Less is known of the changes on the border-line between weathering and replacement of rock constituents than of any other phase of chemical geology. Most alterations of minerals and rocks have been ascribed simply to the action of atmospheric agents, just as formerly the formation of ore- and mineral-veins was ascribed exclusively to the leaching of the country-rocks by vadose waters. Even the most typical post-volcanic formations, such as tin-veins or pegmatite, were considered the results of lateral secretion, and even at the present time most alterations in minerals are ascribed, without further consideration, to weathering.

A cycle of movement for vadose water has been artificially constructed to explain post-volcanic processes, but it is based upon very little actual observation. The carbon dioxide laden water, falling from the atmosphere, is supposed to be able to dissolve and destroy many minerals, primarily by removing their calcium- and alkali-carbonates. It then seeps into the depths through the capillaries of the rocks, its solvent power increasing more and more with increasing temperature. The circulating ground-water, heated or even in part greatly superheated in this manner, is thus supposed to saturate the earth's crust to depths where the critical temperature of water is reached, that is, to approximately 12 km. These heated waters, after withdrawing various substances from the rocks, come together in open fissures, where they are again forced upwards by steam-pressure. As they rise, they gradually cool and lose their solvent power, the dissolved ores are deposited, and the water itself perhaps finally reaches the surface as a mineral-spring.

A strong argument against this hypothesis is the fact that the rocks in all deep mines, even as near the surface as several hundred meters, are dust-dry. This fact seems to show conclusively that ground-water is no longer present at depths giving an increase of less than 20°. A general saturation of the rocks to depths of many kilometers, therefore, is excluded, while the presence of open fissures so far down is highly improbable.

Still another fact shows that most of the deposits cannot be accounted for on the ground-water or lateral secretion theories. Although extremely small amounts of the minerals contained in the tin-veins are undoubtedly present as original constituents in the surrounding granites, it would be remarkable if the vadose waters withdrew from the deep-seated rocks the very minerals, such as cassiterite, tourmaline, etc., which are soluble in them with the greatest difficulty, no matter what the temperature. The problem becomes still more difficult with deposits of sulphide ores, for the associated igneous rocks, when fresh, never contain sulphur. This mineral first appears as a replacement product accompanying ore deposition. Finally, the amount of heavy metals accumulated in certain ore deposits is so great, as compared with that distributed through the country-rocks, that it is necessary to assume the leaching of enormous rock masses, such as are not always at hand, to explain them. Careful observation, therefore, leads to the conclusion that most ore deposits are the results of juvenile agents.

The atmospheric agents, working from above, cover the rocks with a mantle of weathered material. This is usually thin, but it extends to greater depths where fractures in the rock permit the meteoric water to enter, or locally where easily soluble minerals, such as the sulphides, are the source of active agents, as in the gossan of ore deposits. The agents of replacement, however, act from below. Their products form no superficial shell and do not necessarily reach the surface. Replacement phenomena, therefore, are generally of equal intensity at all depths, and are the best criteria of post-volcanic processes. Compact rocks are but slightly permeable by the agents of weathering, the penetration of atmospheric waters being a proof of porosity. The agents of vulcanism, on the other hand, are much more able to attack the rocks on account of the increased temperature and pressure under which they act, and also by their content of chemically active substances which may be present in great quantity. Then, too, the post-volcanic agents may be very rich in these chemically active substances, and while they are local in their action and occur only in close connection with other volcanic phenomena, they are not limited to the superficial parts of the earth's crust.

Attempts have been made to determine the nature of the re-forming processes by the character of the newly-formed products. Cornu advanced the hypothesis that crystalloids result from post-volcanic processes while colloids are produced

by atmospheric weathering. In Chapter V it was pointed out that the most important normal weathering products of the feldspar are doubtless colloids, and the colloidal nature of limonite and numerous other materials of weathering is especially distinct in the gossan of ore deposits.

Cornu's hypothesis fails of broad application, however, as may be easily shown. Where silica, resulting from some vadose process, separates from atmospheric agents, it always takes the form of quartz, as does also the originally amorphous silica of organisms when it appears in fossils. Further, the silica deposited in rocks by atmospheric agents, and in fissures by vadose waters, is always crystalline. On the other hand, silica appears in the form of opal in innumerable post-volcanic processes. In this form it is always associated with certain igneous rocks, and while it may occur in sediments, its origin, in every case, may be directly traced to nearby thermal action.

Innumerable other amorphous silicates such as allophane and gymnite, and the hydrous silicates of nickel, garnierite and pimelite, which are usually amorphous, are found exclusively in areas which have suffered intense post-volcanic metamorphism. The general appearance of talc suggests that it was originally colloidal but later became crystalline. It likewise belongs here, as do also meerschaum and innumerable other magnesium, magnesium-aluminium, and aluminium silicates which are amorphous or in the first stages of recrystallization. Finally, chalcedony, which also appears in connection with volcanic processes, must be looked upon as having been originally amorphous. Amorphous aluminium phosphate, such as turquoise, and the colloidal, porcelain-like, and dense magnesite likewise occur only under conditions which make their formation by juvenile waters probable.

These facts show that it is impossible to separate the two most important processes of rock-destruction on the basis of the crystalloidal or colloidal form of the newly formed minerals.

Formation of Pegmatite.—Pegmatites (Gr. $\pi\hat{\eta}\gamma\mu\alpha$, anything fastened together, on account of the frequent occurrence of graphic granite) are intermediate between true, massive rocks derived from normal, mineralizer-saturated, igneous magmas, and rocks resulting from purely pneumatolytic processes. They are satellites of normal igneous rocks, and have chemical compositions similar to their parent magmas. They are usually extremely irregular in form (Fig. 85), and are found within the igneous rock itself, or in the surrounding contact-metamorphosed zone, in the form of dikes, schlieren, or independent nodules. Where they occur within the parent igneous rock they are usually coarse-grained aggregates of the same constituents as those found in the main mass. They represent a continued growth of the individual

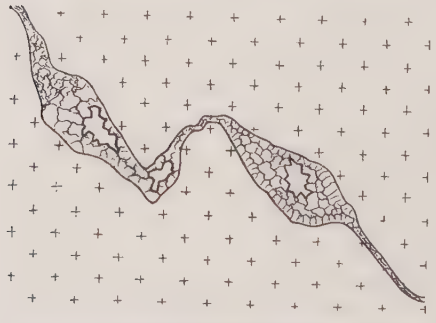

FIG. 85.—Diagrammatic representation of a pegmatite dike.

constituents, and the boundary between the two rocks is blended and indistinct. This, and the irregular shape of the intrusions, show that the pegmatites were formed during the later stages of the solidification of the main mass, and that, with the aplites, they represent the first extrusions after the original igneous activity.

Pegmatites related to each type of plutonic rock are known. They are most commonly and most abundantly developed in connection with granites and nephelite-syenites, but are relatively rare with plagioclase rocks. The more basic the plutonic rock, the simpler are its satellites. The pegmatites normally have aplitic facies, and in places pass through all possible transitions to aplites. But lamprophyres also, here and there, have pegmatitic habits. Coarse-grained portions of kersantite dikes, and some pegmatite-like nephelinite schlieren in basalts, show undoubted affinities with true pegmatites.

Pegmatites have coarse to very coarse textures, and may vary greatly both in texture and composition. Eutectic mixtures, causing parallel intergrowths of the individual minerals, are especially widespread, for example in graphic granite or pegmatite in the narrow sense. The development of gigantic crystals and of crystal-druses suggest the origin of these rocks from magmas especially rich in mineralizers. This mode of origin seems a certainty after a close examination of the minerals themselves and of the intense solvent power which the melt had upon the constituents of the country-rock. In some cases this assimilation of foreign constituents was so great that it altered the entire character of the rock.

A careful examination of the minerals of the pegmatites shows that there must have been a remarkable concentration of mineralizers, and that the so-called rare elements, which are present in normal rocks only in traces, are very abundant.

The minerals of the pegmatites may be grouped as follows:

1. The minerals of the parent rock, namely: quartz, orthoclase, albite, and white and more rarely dark mica; and in certain rocks, anorthoclase, nephelite, sodalite, etc., with ægirite and arfvedsonite.

2. Minerals containing especially active elements: tourmaline, topaz, fluorite, scapolite, and apatite.

3. Minerals containing rare elements: monazite, xenotime, orthite, beryl, chrysoberyl, niobates and tantalates, molybdenite, zircon, titanite, and, in nephelite-syenite pegmatites, the zirconium silicates, especially låvenite, mosandrite, rinkite, astrophyllite, katapleite, etc.

4. Minerals derived from the country-rocks: andalusite, disthene, garnet, cordierite, staurolite, and the like.

To these must be added occasional ore-minerals, and, as final products showing the gradual transition into the thermal stage, various zeolites and some opal.

This extraordinary paragenesis occurs only in the alkali-rich rocks. The pegmatites of the plagioclase series are much simpler, in many cases being merely coarsely developed phases of the parent rock. Crystal-druses are usually very abundant in granite-, syenite-, and nephelite-syenite-pegmatites, and there may be a remarkable development of beautifully crystallized minerals; in the plagioclase-pegmatites, druses are rarely present.

Pegmatites rich in tourmaline, scapolite, etc., may impregnate the country-rock with these minerals to a considerable distance. Ordinarily, however, the minerals developed depend to a large extent upon the composition of the country-rock. For example, where the granite-pegmatites of the Bavarian Forest pass into the aluminium-rich contact-rocks, large druses containing andalusite are developed. In the Fichtelgebirge a similar rock cuts eclogite and becomes a coarse-grained aggregate of feldspar and zoisite. In other regions the constituents dissolved from the country-rock form staurolite, garnet, disthene, etc. The orthoclase content of these dikes is readily lost and albite takes its place, in many cases becoming an important constituent.

That there is a connection between the pegmatites and vulcanism has been denied on the strength of these abnormal relationships, and these rocks have been ascribed to lateral secretion, that is to the leaching of the country-rock by circulating water. The manner of their occurrence, however, is decidedly against this view, and their intimate connection with igneous rocks is too apparent. Furthermore, they do not bear the slightest resemblance in texture or composition to deposits from vadose solutions.

Further modifications may be produced in the pegmatites by the action of piezo-crystallization. In many cases masses of alkali-mica scales take the place of the feldspars, and normal pegmatite dikes, which extend for long distances, may grade into schistose aggregates of mica closely resembling mica-schists. The drusy texture is then usually entirely wanting. Such modified pegmatites, carrying staurolite and disthene derived from the contact-metamorphosed country-rock, occur in the Tessin (Ticino) paragonite-schists. On the other hand, perfectly normal pegmatites are found in the central granite. Like the mineral-rich dikes of the Titan-formation, which cut similar rocks, they contain innumerable druses filled with magnificent crystals. This drusy condition indicates a cessation of pressure during their formation; in fact, the dikes intruded immediately after the main granite of the central Alps show in many places that orographic forces were absent.

The Amygdaloids.—Vesicular and scoriacious rocks, with their cavities entirely or partially filled with secondary minerals, are widely distributed among dike-rocks, especially among lamprophyres. They also occur among the extrusives, and are as common among basic rocks as among silicic. Such rocks (Fig. 86) are called *amygdaloids* (Gr. ἀμυγδάλη, almond). While their characteristic paragenesis has usually been ascribed to lateral secretion, whereby the mineral-matter is supposed to have been deposited from solutions leached by atmospheric agents from the country-rocks, as a matter of fact these minerals are predominantly those which elsewhere are universally associated with igneous rocks, and which have never been known to be deposited from vadose waters.

Among the amygdule fillings, chalcedony and the zeolites are especially interesting. These minerals are elsewhere known only in connection with hot juvenile springs, and therefore probably have a similar mode of origin where they fill the vesicules. Most typical occurrences are agate-amygdules. These vary in size from a few millimeters to over a meter, and their banding (Fig. 87) clearly shows the gradual filling of the cavities. Various features suggest that the chalcedony was originally gelatinous and later became crystalline. In many cases the agate-amygdaloids are hollow and lined with quartz crystals, commonly amethyst, a form of quartz which is never of unquestionable vadose origin. Among other minerals occurring in this manner are calcite and aragonite, various zeolites, here especially well developed, prehnite, boron-bearing datolite, and, in certain melaphyres, abundant native copper. Scaly hematite and goethite are also present. Further, green substances of various kinds, such as seladonite or chloritic minerals, are abundant in the vesicules, and with them, in many cases, epidote or different colloidal silicates. These minerals are found not only in the vesicules of the lava-streams but also in the larger cavities of bombs lying in volcanic tuffs, and here and there in fissures.

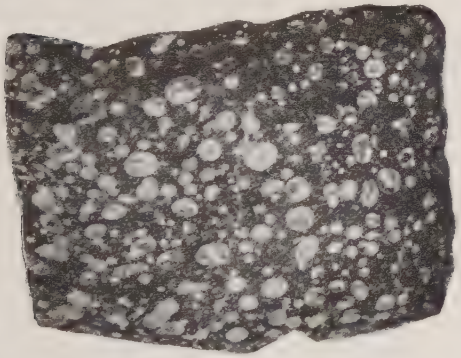

FIG. 86.—Melaphyre amygdaloids. Oberstein a. N.

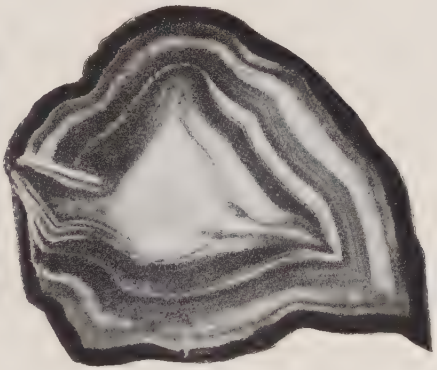

FIG. 87.—Agate showing conduit. Oberstein a. N.

The vesicular character of the lava is doubtless primary and due to the escape of the gaseous mineralizers during the solidification of the rock. Besides these rounded vesicules, however, there are found in the effusive rocks many other cavities which are of irregular shapes and appear to be due to corrosion. These cavities probably originated in the dissolving action of gases during the last stages of the solidification of the magma, and in them, minerals of an entirely different kind are deposited. Thus, tridymite and topaz are found in rhyolites and trachytes, while well-developed crystals of sanidine, nephelite, sodalite, leucite, melilite, etc., as well as olivine, pyroxene, amphibole, and locally calcium-magnesium garnets, and even the rare lievrite, occur in the soda-rocks. Probably all of these minerals are of pneumatolytic origin, and water had little to do with their formation. The local occurrence of opal, however, shows that pneumatolysis was sometimes combined with the hydration of the thermal period.

Finally, there remain to be mentioned certain peculiar, mostly colloidal phosphates which occur predominantly in fissures of volcanic rocks, and which unquestionably also belong to the post-volcanic thermal period. The turquois deposits in trachytes and trachyte tuffs of Persia and the amorphous phosphorite films on the parting-planes of many basaltic columns are of this kind.

Mineral-dikes and Ore-veins.—By far the greater number of fissure deposits of minerals and ores are of juvenile origin, and while certain ore deposits may be far removed from any igneous rocks, an examination of their general relationships very rarely shows them to be of vadose origin. Most mineral-dikes and ore-veins are of less importance in petrology than they are in mineralogy and economic geology, therefore only a few especially typical examples will be cited.

Tin deposits are the most noteworthy and typical representatives of the pneumatolytic period of volcanic activity, a period characterized especially by mobility of gases under high pressure. These gases, emanating from the magma and loaded with powerful mineralizers, penetrated fissures and dikes, and generally saturated the country-rocks to great distances. The ore deposits are genetically connected with

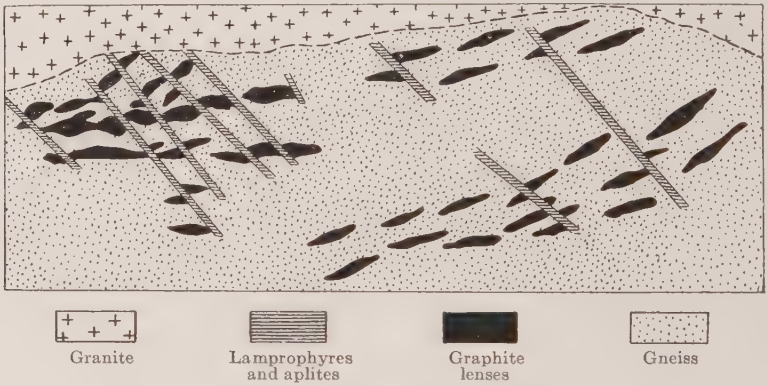

FIG. 88.—Occurrence of graphite lenses in the neighborhood of Passau.

granitic rocks which either contain a very small amount of tin and other minerals of the dikes (tin-granite), or whose mica carries lithium (lepidolite-granite or its porphyritic equivalent, lithium-bearing quartz-porphyry).

The nature of these ore-bearing dikes is well shown by the extent of the mineralization of the country-rocks, for whether the walls are granite, granite-porphyry, or quartz-porphyry, or injection-schists or other contact-rocks, they are impregnated to a considerable distance by quartz, tourmaline, topaz, fluorite, and other minerals of the tin formation. Most noteworthy is the fact that the feldspar of the original granite has disappeared, and topaz- and fluorite-rich *greisen* is formed. In the granite-porphyry called *luxullianite*, the groundmass is changed to a dark, tourmaline-quartz aggregate, the larger feldspars either remaining unaltered or becoming changed to tourmaline, topaz, or tin ore. Many rocks have been altered to tourmaline- or topaz-rich quartzites (*zwitters*), while the entire feldspar content of others has become kaolinized. All rocks, irrespective of their original character, show alterations of this kind, and everywhere near the dikes, cassiterite and its constant companion, arsenopyrite, occur as impregnations. Farther from the dike the normal, unaltered rock appears.

Among ore-veins none furnishes a stronger argument against the lateral secre-

tion theory than does cassiterite. Here, contrary to the theory, the country-rock has in many cases been altered by the action of true fumaroles to a considerable distance from the dike, and the ore formation was everywhere accompanied by the formation of tourmaline and topaz, which were no more deposited from vadose circulating solutions than was the cassiterite itself. The phenomena connected with tourmaline-bearing copper-ores are analogous, and zwitter and greisen are developed, although to a less extent.

The effects of post-volcanic processes are very characteristically shown by certain graphite deposits, especially by those occurring in dikes in the granulite of Ceylon, and by the graphite-gneiss which is found in small lenses in injection-schists near the granite-contact at Passau, Bavaria (Fig. 88). In the latter especially, the action of volcanic agencies is very clear. The parts rich in graphite represent impregnations of the injection-schists, for wherever graphite occurs they are more or less completely altered to kaolin, nontronite, and amorphous silicates of manganese, and in many cases are impregnated with opal.

Injection-schists are ordinarily very compact rocks and form steep cliffs, but in the graphite area they are altered to unconsolidated earth. On the other hand, the younger lamprophyre and aplite dikes, which cut and fault the graphite lenses, have

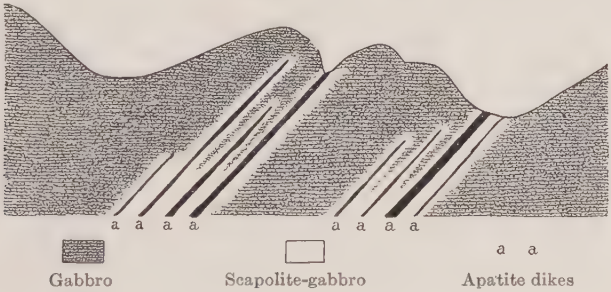

FIG. 89.—Apatite dikes with scapolitized gabbro. Husaas, Norway. (After J. H. L. Vogt.)

remained unaltered in spite of their high pyrite content. There can be no question as to the secondary character of the graphite in the injection-schists, nor of the intimate relation between the intense metamorphism and the formation of the graphite. The large amounts of iron and manganese which are present can only have been brought in with the graphite, for since these metals occur in their highest states of oxydation they cannot be ascribed to reducing agents. Probably most of the graphite was brought in as unstable carbon compounds, which easily broke up into carbon dioxide and oxides of the metals. At any rate, these graphite deposits are due to post-volcanic processes.

The alterations in the country-rock around the rutile-apatite dikes of South Norway also point to intensive post-volcanic processes. The country-rock is a normal gabbro, but near the dikes it is impregnated with chlor-scapolite, and in many cases is entirely altered to a hornblende-scapolite rock filled with rutile and apatite (Fig. 89).

The central Alpine Titan formation is somewhat different in appearance, but it is very intimately related to the pegmatites of the central granite. Here the country-rocks had a great influence upon the dikes. This influence can be explained only on the assumption that hot gases had less to do in changing the character of the dikes than had heated solutions, which dissolved considerable material from the surrounding rocks. The dikes are characterized by the constant presence of titanium oxide,

although this does not occur in quantities great enough to be of commercial importance. Where the dikes cut the granite, the chief constituents are quartz and adularia, with rutile, anatase, and brookite. In many cases these minerals form beautiful crystals, and the so-called Crystal Cellar of the Alps occurs in this part of the formation. Toward the contact-zone, prehnite, zeolites, and titanite, and farther on diopside, zoisite, and epidote occur in the dikes. Where they pass into amphibolite or greenstone-schist the latter three minerals become the chief constituents, the quartz disappears, and in place of adularia, beautiful crystallized albite is developed. In many places minerals characteristic of the pegmatite itself also appear, among them are monazite, beryllium-bearing euclase, tourmaline, some fluorite and apatite, ore-minerals of many kinds, and even native gold. The dikes become still richer in minerals where they traverse any of the numerous serpentine stocks of the region,

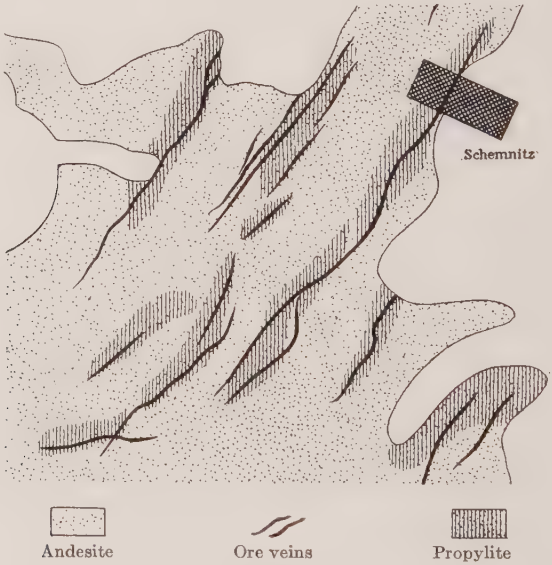

FIG. 90.—Sketch map of the neighborhood of Schemnitz, Hungary.

as was shown on page 133. The influence of the intrusives upon the country-rock, on the other hand, is at most very slight.

Opposed to these processes, in a certain way, are the replacement processes in the dikes of the so-called propylitized gold-silver formation. Various igneous rocks, chiefly andesites, are impregnated with pyrite adjacent to the ore deposits. They are also otherwise altered to greater distances, yet never outside the zone of influence of the dike itself (Fig. 90). This alteration process is called *propylitization*, and by it the original anhydrous minerals of the igneous rocks were altered to hydrous minerals such as chlorite, sericite, kaolin, etc. *Propylite* (Gr. *πρόπυλον*, entrance, since the rocks were supposed to be the earliest extrusives of the Tertiary igneous cycle) was formerly supposed to be an independent kind of rock, intermediate between the older and younger igneous rocks. It actually is only an altered variety of andesite, and perfectly fresh rock occurs farther from the dikes. Propylitization is a form of pneumatohydatogenic alteration in which the country-rock had no influence upon the character of the dike.

Varieties of Rock Alteration.—The replacement phenomena associated with these secondary formations are transitional to true post-volcanic metamorphism. The characteristics of the latter as a deep-seated process, and the differences between it and weathering have been mentioned previously. The local causes for replacement are very variable, as is also the ability of the different minerals to resist the different processes, consequently the course of the reaction itself and the results to which it leads are also variable. Minerals which can best withstand weathering are in some cases easily destroyed by replacement, and the contrary is just as commonly true. Tourmaline and disthene, for example, may be altered to mica-like substances by post-volcanic agents, but they are entirely unaffected by simple weathering. Again, biotite, monazite, and xenotime are absolutely fresh in completely kaolinized granites, yet they are very readily decomposed by weathering.

The most important post-volcanic metamorphic processes are the following:

1. *Kaolinization.* Kaolinization is probably one of the most characteristic of replacement processes, and is of rather widespread occurrence. It is of most importance in granites and quartz-porphyries, but takes place in other rocks, and is even present in very basic varieties. The alteration normally appears in isolated, larger or smaller patches, or in a series of such patches along a fissure. It differs from weathering in that it primarily attacks the feldspar, acting upon plagioclase more readily than upon orthoclase, but scarcely affecting microcline.

Weathering changes granite into rusty grush in which the alkali content remains high, but kaolinization completely removes the alkali as well as the lime from both plagioclase and orthoclase. Biotite is usually the first mineral to be affected by weathering, but it is fresh in many kaolinized rocks. It is especially characteristic that apatite, which is unaffected by chemical weathering, disappears completely under the action of kaolinization, and monazite and xenotime, which become cloudy upon the slightest weathering, are always clear and fresh in kaolin.

The kaolinized patches in granite, even directly at the surface, laterally pass abruptly into normal rock. In depth, on the other hand, and this must be especially emphasized on account of innumerable assertions to the contrary, such a transition can nowhere be seen. It is true that drill-holes may show compact granite below the kaolin, but this is probably due to the irregular form of the kaolinized patches, as is shown in Fig. 91, in which the broken lines represent three drill-holes. Where the degree of kaolinization alters, it invariably increases with depth, even to 400 to 500 meters, where atmospheric agents must of course be absent. Nests of tourmaline are not uncommon in kaolin deposits, and the purest kaolin occurs in their vicinity.

Furthermore, mechanical rock analyses show the presence of a small quantity of tourmaline, topaz, fluorite, pyrite, and siderite in numerous kaolin deposits, and these minerals, which do not occur in the original rocks, indicate the nature of the agency which produced the change.

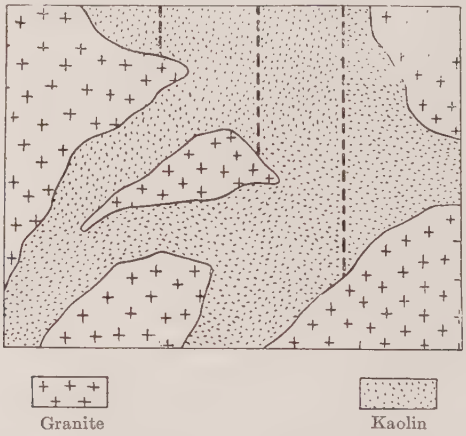

FIG. 91.—Ideal section through a kaolin deposit in granite.

Many kaolinized rocks are associated with deposits produced by pneumatolysis, a process which always produces intense alteration in the accompanying rocks. Thus propylite, and rocks within the sphere of influence of some graphite deposits or cassiterite dikes, are altered to kaolin in the last stage of replacement. Furthermore,

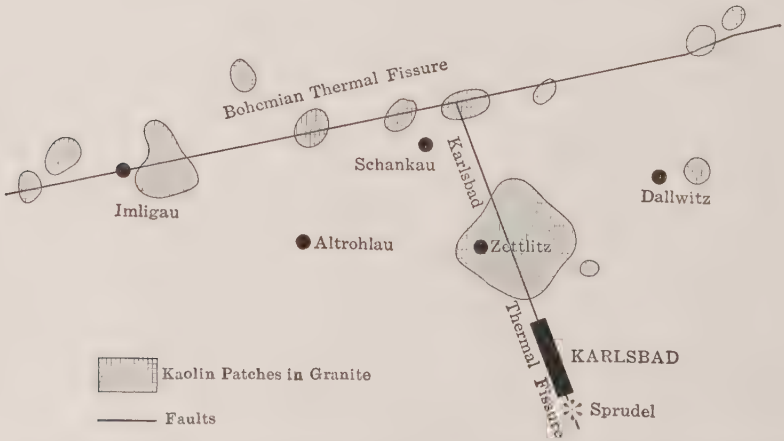

FIG. 92.—Sketch map of the neighborhood of Carlsbad. Shows the relationship between the kaolinized patches and the fault lines.

near many kaolin deposits, as at Karlsbad in Bohemia (Fig. 92), there are active hot springs even at the present time, and the relationship between the two is very clear. The fact that pegmatite and aplite are kaolinized in so many cases and so intensely shows the activity of the gases and vapors producing this type of alteration.

2. *Saussuritization, uralitization,* and the formation of greenstones, are alteration phenomena in basic igneous rocks, but, as was shown on page 131, they may also appear in granite itself as the result of contact-metamorphism. Alteration may take place, however, without the influence of foreign plutonic rocks, as was shown under the discussion of propylite, a rock belonging to the greenstone series. Under such metamorphism, the original texture of the rock generally remains quite distinct. The feldspar, in some cases, is altered to a dense aggregate of saussurite, and such greenish, saussuritized porphyrites and other similar rocks are among the toughest and most resistant of rocks. Besides the calcium-aluminium silicates which compose the saussurite sericite and calcite may occur, and in some cases, as in normal greenstones, may predominate in amount. In such cases, the pyroxene is rarely truly uralitized, but is changed to an aggregate consisting chiefly of chlorite with some epidote and perhaps a little uralite. Primarily the process is one of hydration and decalcification. An impregnation by pyrite is always associated with the formation of greenstone, and pyrite is probably always secondary in saussuritized and uralitized rocks.

Greenstones are most commonly formed from silica-poor rocks. They are rarely formed from those that are rich in silica, and apparently never from sodic rocks. Dikes and extrusives are most subject to this alteration; among the former, lamprophyres, and among the latter, andesite and porphyrite, trap, and melaphyre are especially susceptible.

Two entirely different types of alteration may be distinguished among these rocks. In the first type, the rocks, which are gray or brownish black when fresh, become brown, brownish red, or red. These are the usual colors of altered quartz-porphyries, and they are not uncommon among basic porphyrites and melaphyres. The originally compact rock eventually acquires an uneven fracture and loses its luster, and its marked clay-like odor has given rise to the name clay-stone porphyry. Finally, the rocks take on a dull uniform color, and form masses which are distinguishable with difficulty from each other. They were called wacke by the earlier geologists. The final phase of this alteration process makes the rock character unrecognizable, and is doubtless due to atmospheric agents. Whether the beginning of the alteration, which is marked by an intense impregnation with iron oxide, is due to the same cause, must still be considered questionable.

The alteration shown by greenstone-porphyry and diabase is quite different. Here the entire process was doubtless one of true replacement by means of hot juvenile waters, which were probably always sulphur bearing, as seems to be indicated by the constant presence of pyrite in rocks so altered.

The formation of saussurite has often been considered typical of dynamometamorphism on account of the relatively high specific gravity of the calcium-aluminium silicates which are present in it. As was shown above, most saussuritized rocks result from contact-metamorphism. The alteration is not necessarily connected with

especially intense tectonic processes, but depends upon causes similar to those producing greenstones, the difference being due perhaps to greater depth and pressure during the process of replacement. More hypabyssal and plutonic rocks than extrusives, therefore, are saussuritized, while there are more greenstones derived from extrusives.

3. *Sericitization* in acid rocks corresponds somewhat to the formation of greenstone from those that are basic. Sericitized aggregates derived from feldspars occur even in the latter, while chlorite is widely distributed in sericitized granites or quartz-porphyries. Sericite occurs locally in the Erzgebirge at the contact between granites, gneisses, and quartz-porphyries and veins of silver-bearing galena, the formation of the latter having produced the alteration in the former. It also occurs where rocks show considerable faulting, for example in the Bavarian Forest where the granite is altered to the Pfahl schist, a rock consisting of finely brecciated quartz separated by fine sericite films.

The micaceous character of the alteration is especially distinct in the fine, silky-lustered, light-colored sericite-schists produced from crushed quartz-porphyries. In these rocks, which in many cases have paper-thin schistosity, the rounded or embayed quartz phenocrysts of the former quartz-porphyry may still be recognized, and they may even be visible megascopically as small, hard knots on cleavage surfaces of the crinkled rock.

Sericitization also has frequently been considered a dynamometamorphic change, and it is undoubtedly true that, in numerous cases, mechanical forces have assisted in the alteration. Probably the most characteristic examples are offered by the Pfahl schists and certain poryhyroids occurring in the strongly folded Paleozoic rocks of the Taunus and the Ardennes, the latter having been altered to sericite-schists where mashed to an exceptional degree. That thermal activity was here of great importance is shown by the enormous quartz-dikes (and their accompanying minerals) which are associated with the Pfahl schists and with other closely related alteration products of the crushed granite. In other cases, however, sericitization has altered quartz-porphyry to a silky-lustered, white schist without producing any observable deformation in the quartz phenocrysts. Many such schists are interbedded with contact-rocks, and it is probable that the sericitization of the quartz-porphyry is here due to contact-metamorphism. It is hardly necessary to say that quartz-porphyry-tuffs under analogous conditions are similarly altered, so that after metamorphism the igneous rock cannot be separated from its tuff.

4. *Serpentinization.* The formation of serpentine from olivine-rocks may be traced in most cases to the action of contact-metamorphism, as described on page 132. Some serpentines, however, may have originated from originally anhydrous olivine-rocks by thermal processes following their intrusion, just as certain greenstones originated by a similar process. Nevertheless, large

mountain-making masses of serpentine are certainly not products of normal weathering, and just as little are they the results of dynamometamorphism. The attempt has been made to assign different modes of origin to the two varieties of serpentine; antigorite, which occurs principally in folded mountain regions, is regarded by some as the result of the orogenic forces, while chrysotile is assumed to be the normal product of weathering.

Serpentine [$(Mg,Fe)O : SiO_2 = 3 : 2$] may be regarded as consisting of one part olivine [$(Mg,Fe)O : SiO_2 = 2 : 1$] and one part bronzite [$(Mg,Fe)O : SiO_2 = 1 : 1$], but it is doubtful if olivine and bronzite in these proportions ever resulted in the formation of serpentine. Most serpentines originated from peridotites, that is, from rocks in which olivine greatly predominated, and this fact alone shows that the formation of serpentine is a more complicated process than is usually supposed since a considerable amount of silica must be added or great amounts of magnesia and iron subtracted. Furthermore, the development of other new minerals, such as talc, actinolite, chlorite, and carbonates, indicates that the process is not simple.

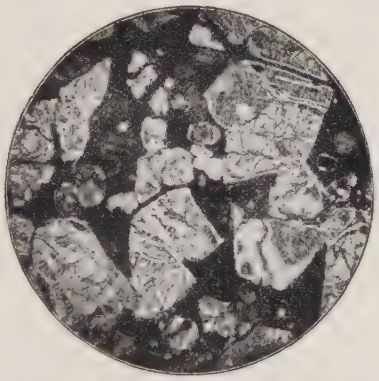

FIG. 93.—Serpentinized olivine crystals in picrite. Trogen, near Hof, Fichtelgebirge.

With the exception of a few unimportant contact-metamorphosed carbonate-rocks, all serpentines were derived from rocks originally igneous. In innumerable cases they accompany greenstones and greenstone-schists, which are undoubtedly of igneous origin, and they are widespread as dikes. It is true that serpentines generally form lens-shaped beds intercalated between other rocks, but where they are interbedded with limestones and marls, they are surrounded in many cases by normal contact-rocks.

Like the accompanying greenstone and saussuritefels, serpentine is probably never an original rock. Although in some cases it has been considered original, microscopic examinations almost invariably show, by the more or less abundant remnants of the anhydrous silicate still present, or by the mesh texture of the chrysotile or the grating texture of the antigorite, that olivine was the chief original constituent.

Where olivine occurred as a subordinate constituent in such rocks as gabbros, traps, melaphyres, and basalts which have been serpentinized, its outlines are still well preserved. In true serpentine masses such well-bounded pseudomorphs are wanting, the original rock having consisted originally of an equigranular aggregate of olivine. Porphyritic olivine-rocks are extremely rare, but where they do occur, the phenocrysts with their mesh structure and the preserved remnants of the original mineral, stand out distinctly from an extremely dense serpentine groundmass (Fig. 93).

5. The *formation of talc* must be considered here as an appendix to serpentinization, since talc may be produced by this process as

an accessory mineral. Talc differs from serpentine, which is derived almost exclusively from olivine, in being an alteration product of many minerals, magnesia-bearing and magnesia-free, silicate and non-silicate. It may be formed from olivine-rocks as well as from dolomites, from limestones as well as from granites. Even true slates may be re-formed into pure talc-rocks. This most radical replacement process uniformly attacks everything that comes within reach of the re-forming magnesia-rich solutions, and is rather widespread in the contact-zones of granites, where such solutions are always strikingly abundant. Important deposits of compact talc which were formed in this manner in all probability originally consisted of the colloidal alteration products of various minerals and rocks at the granite contact. Where talc-rocks occur as patches and dikes in serpentine, they are more distinctly crystalline than they are elsewhere.

In many cases much chlorite is developed simultaneously with the talc, as in soapstone, which occurs in granite as well as in serpentine. Furthermore, many of the granites in the neighborhood of the talc beds of the Fichtelgebirge are intensely chloritized, and pseudomorphs of chlorite after orthoclase are not uncommon. Finally, in completely mashed granites, such as the so-called Winzer granite on the banks of the Danube east of Regensburg, the entire feldspar content is in many cases altered to a dense aggregate of chlorite.

6. *Zeolitization* is a replacement process which primarily attacks nephelite, leucite, and minerals of the sodalite group. That this alteration is also due to thermal action is shown by the fact that zeolitized and perfectly fresh rocks occur side by side in places where the hydrographic conditions are the same.

The phonolite domes of Hohentwiel in Hegau, which are especially well known because they carry natrolite, are penetrated by a well to a depth of 100 meters, and all of the rocks taken from it are uniformly zeolitized, yet very small ejected fragments of the same rock in the surrounding tuffs contain no zeolites, even at the surface, but instead carry considerable amounts of perfectly fresh hauynite and noselite.

7. Besides these ordinary phenomena of post-volcanic metamorphism, others of purely local character should be mentioned, such as the alteration of rhyolites and rhyolite tuffs to alunite, and the formation of potash-rich seladonite in potash-free melaphyres. In both cases there has been a great addition of material such as could not have been brought about by the usual agents of weathering.

The silicification of rhyolites and quartz-porphyries or their tuffs, and the development of chalcedony and opal in all kinds of igneous rocks, their tuffs, and the adjacent sediments, belong to the same group of post-volcanic processes. Silicification by weathering, on the other hand, generally produces a quartz-cement, yet such cement

may be also abundantly produced by post-volcanic processes. This may be seen, for example, at numerous contacts between diabase and silicified adinoles and lydites. The formation of bauxite is of a different character, for here great amounts of silica are removed, an alteration also observed in some basic igneous rocks.

8. *Metasomatic Replacement of Carbonate-rocks.*—The constituents of carbonate-rocks, especially of limestones, are readily soluble in various solutions, and from these solutions new minerals crystallize. Thus ores or minerals which have originated through replacement are very widely distributed in limestones, and are spoken of

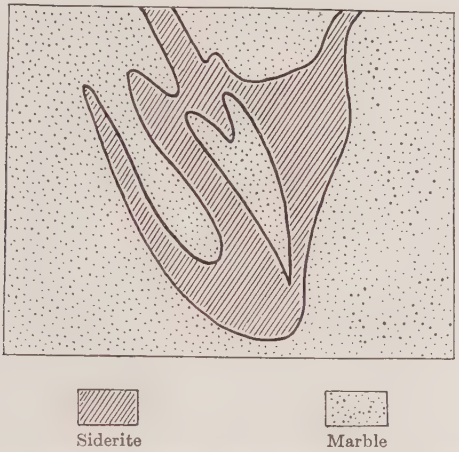

FIG. 94.—Irregular form of a siderite patch in marble. Hüttenberg, Kärnten.

as *metasomatic* (Gr. μετά, after, σῶμα, body). These deposits are extremely irregular in shape (Fig. 94), and may be rather sharply separated from the unaltered limestones or may be connected with them by transition zones.

Numerous deposits of siderite, rhodochrosite, and magnesite, which are very abundant in the altered limestones of the contact-zone of the central Alpine granite, belong to this class. The analogous silicate skarn deposits with magnetite, manganese silicates and oxides, or zinc oxide, etc., were already mentioned on page 129. Finally, sphalerite, galena, and calamine may occur under similar conditions, as do also the silica deposits in greenstone-schists and amphibolites.

IX. REGIONAL METAMORPHISM

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Early Ideas Regarding the Crystalline Schists.—Geologists long ago recognized the existence of a fundamental difference between the so-called fossiliferous rocks and certain unfossiliferous *crystalline schists* which combine the characters of bedded and crystalline rocks. Many of the latter were definitely known to be of great geologic age, therefore, on the basis of their petrographic characters, the generalization was made that *all* schistose crystalline rocks must belong to the same primitive Archean formation, a formation supposed to consist of the oldest sediments of the earth.

With further study in the provinces which were best known at that time, this "primary" schist group was subdivided into gneiss, mica schist, and phyllite. Each of these rocks was supposed to be as characteristic of a time-division in the history of the earth as any of the later fossiliferous formations. Since these old deposits were unfossiliferous, their separation is necessarily purely petrographic and depends primarily upon the fact that the gneisses, which are the very oldest formations, are chemically allied to granitic rocks, while the other two groups are analogous to later clastic sediments. Furthermore, there appears to be a gradual decrease in the crystalline character of the rocks from the gneisses to the phyllites, and most of the upper members of the latter group appear to be transitional to clastic rocks.

The assumption that the Archean represents the original crust of the earth and the first chemical precipitates deposited upon it, appears at first sight to be the simplest and most natural explanation, and the fact that the crystalline schists were universally present wherever deep cuts exposed the base of the fossiliferous formations, was formerly especially emphasized. Furthermore, it was generally found that the different members of the crystalline schists were the same everywhere, and they occurred in the same sequence—gneiss, mica-schist, and phyllite—as they necessarily should if they represented the oldest formations of the earth's crust.

The innumerable inconsistencies which careful study reveals between the actual relationships and these theories might easily be overlooked on a superficial investigation of the crystalline schists. Because some crystalline schists are unquestionably pre-Cambrian, all have been assigned to this age, yet in by far the most localities

they are overlaid, not by the oldest fossiliferous sediments, but by very much younger ones, into which the schists in many cases pass by gradual transitions. On the other hand, the true sediments of the Cambrian, and those of the pre-Cambrian carrying occasional fossils, are by no means the oldest, non-crystalline formations of the earth, for in South Africa there is a whole series of non-fossiliferous sediments whose clastic characteristics are hardly altered, yet in it may be recognized a long period of pre-Cambrian sedimentation, divided into epochs by numerous well-developed unconformities and transgressions.

Younger Crystalline Schists.—Because most crystalline schists contain no fossils, they were thought to have been formed before organic life was possible upon the earth, hence the term *Azoic* (Gr. α, without, $\zeta\omega\grave{\eta}$, life) was applied. Even so long ago as the beginning of the last century, occasional fossils had been found in rocks with the petrographic character of normal crystalline schists. This fact, however, did not disturb the belief in the non-fossiliferous character of the old crystalline schist formation, for the fossils were not especially primitive but could be correlated with certainty with type-fossils of younger geologic epochs. Thus the Silurian graptolites in the mica-schists of the Bergen peninsula in Norway, the Jurassic belemnites in those of the St. Gotthard region, and the Carboniferous plant remains in the phyllites of the Low Tauern mountains, are all similar to the type-fossils and show that these schists unquestionably belong to post-Archean formations. Elsewhere, gneisses and other crystalline schists are found interbedded with younger formations, for example in the Cretaceous in Attica.

These "younger" crystalline rocks, consequently, were differentiated from the so-called Archean schists by their fossils, and enormous faults were artificially established, especially in the Alps, to separate the "true" crystalline schists from these later imitators. In petrographic character these younger crystalline schists correspond so completely in every particular with those regarded as Archean, that from this standpoint alone they must be considered identical. By so regarding them, however, the whole basis for classifying the "crystalline schists" as a single formation, namely on their petrographic character, is destroyed. Here, as everywhere, the fundamental law of petrography holds: *petrographic character and geologic age are in no way related.*

The subject cannot be dismissed without mentioning the fact that there have been found locally in the crystalline schists, certain structures which seem to represent organic remains, and which differ from all known fossils. For a long time these were regarded as examples of the earliest organisms which had existed upon the earth.

One of these apparent fossils is Eozoon Canadense (Fig. 95). This consists of serpentine and calcite so intergrown that it externally resembles certain organic structures and therefore was long thought to be a variety of primeval, giant foraminifera, coral, or something of that nature. Careful examinations of material from the original locality, Petite Nation, Canada, and of all similar ophicalcites from Europe, have clearly shown, however, that they are all contact-metamorphosed, forsterite-bearing limestones and not of organic origin.

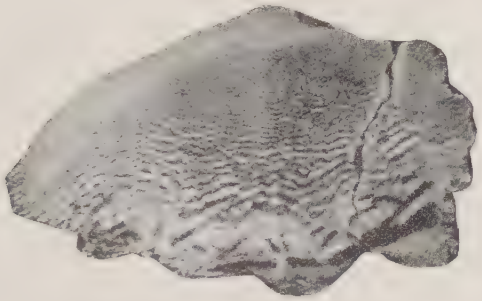

FIG. 95.—Eozoon Canadense. Ophicalcite from Petite Nation, Canada.

During the long controversy regarding the organic nature of these rocks, a noteworthy microscopic feature of the Canadian occurrence was overlooked, although just this feature simulated the organic structure, namely, a worm-like intergrowth of dolomite and calcite (Fig. 96), somewhat resembling pegmatitic intergrowths of quartz and feldspar. Like these, it probably represents a eutectic mixture. Futhermore, absolute proof of the great age of the Laurentian deposits in which the Eozoon Canadense was found does not appear to have been given, the age assumption resting upon the petrographic character of the rocks.

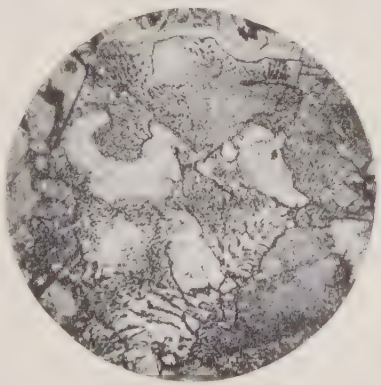

FIG. 96. Eutectic intergrowth of calcite and dolomite in Eozoon. Petite Nation, Canada.

It is noteworthy that all the known fossils of the crystalline schists, so far as their ages have been determined with anything like certainty, belong to relatively young geologic formations. An examination of these so-called oldest sediments in various localities leads to the conclusion that they are unquestionably not the oldest fossil-bearing sediments. The same conclusion is reached by a study of the life development in the Cambiran, its well-developed fauna showing that it must have been preceded by a long series of more primitive forms. Nowhere in the crystalline schists, however, have fossils bearing the characteristics of primeval forms been found. This has been explained as being due to the lack of resistant hard parts in these primitive forms, an explanation also given for the fossil-free character of the extensive pre-Cambrian formations of South Africa.

If, however, conclusions derived from historical geology are justifiable, there can be no doubt that Cambrian fossils must have had a long series of ancestors with preservable skeletons. That they have not been found has always been a stumbling-

block to geologists, and it seems impossible to explain their disappearance except on the assumption of great disturbances of the earth's crust at the beginning of the Cambrian, perhaps corresponding to the Catastrophic Period of Stübel.

Variability of the Crystalline Schists.—The great variability in the composition of the different members of the crystalline schists series has already been pointed out. It is so pronounced that it can be overlooked only on the most superficial examination. It is true that the rocks of one formation are embraced under the name of gneiss, but the name is more geologic than petrographic, and if the rocks are examined carefully, all ideas of even approximately similar characters must be dismissed at once.

The individual members of the gneiss series have only two properties in common: (1) they have a more or less clearly recognizable parallel structure, and (2) they usually contain the minerals quartz, feldspar, and mica. The gneisses of the Alps, the Bavarian Forest, the Erzgebirge of Saxony, etc. are so very different in texture, in the occurrence of accessory minerals, and in the relative proportions of the chief constituents, that geologists accustomed to work in one region are hardly willing to regard the rocks in another as equivalent formations.

Furthermore, innumerable rocks, granular limestones, gabbros, eclogites, amphibolites, serpentines, or ores, are interbedded with the gneiss, either in schistose or lens-like masses, or forming an entire horizon, as granulite does in the Saxon Granulitgebirge, in Bohemia, and elsewhere. In short, the whole appearance of the formation differs from that which one naturally would have expected of the first solid crust of the earth.

The conditions in the mica-schist formation are still more confused. Besides the mica-schists proper, all of the characteristic rocks of the gneiss formation, amphibolites, chlorite-schists, greenstone-schists, calcareous-mica-schists, quartzites, etc., again appear. The same variability, though to a lesser degree, is characteristic for the phyllites, the upper group of the crystalline schist formation.

A thorough geologic and petrographic study of the crystalline schists shows, without question, that these rocks by no means represent a universal formation. The only characteristic common to all of them is their variability and not their uniformity, although the latter might be presupposed as an essential of the earliest crust of the earth. It follows, therefore, that the crystalline schists cannot be portions of this primeval crust.

Gümbel's Theory of Diagenesis.—Gümbel attempted in a measure to overcome the difficulties brought out by the characters of these rocks by means of his theory of *diagenesis* (Gr. διά, through, γίγνομαι, to be born). According to this theory, the crystalline schists, which were originally normal, clastic sediments, have undergone much greater alteration than the sediments of later geologic formations. This is due primarily to the fact that the water of the earliest periods, on account of its higher temperature and greater content of chemically active agents, had a much greater power to dissolve and rebuild than it had later. The recrystallization of the ooze, thoroughly saturated as it was with hot sea water, to gneiss or mica-schist is hard to understand, especially when the unimportance of diagenesis in later formations is considered. And furthermore, only the insoluble residues were left to be re-formed by diagenesis, the primeval ocean having undoubtedly leached and precipitated elsewhere some of the materials from the particles of ooze still floating in it.

The theory of diagenesis depends upon the assumptions that all of the formations embraced in the Archean group represent one definite time period, that they were deposited before the oldest fossiliferous strata, and that during this time the physical conditions at the surface of the earth were not as yet suitable for life, or, if they were so, only for very low forms. These assumptions are accepted as a matter of course by most geologists, although the existence of crystalline schists of definitely-known younger age alone should serve as a warning that care must be taken in using petrographic characteristics as indicative of definite age relationships.

The crystalline schists of the Pyrenees which are overlaid by Upper Silurian beds, and the formations of the Central Alps overlaid by Triassic and Jurassic, cannot be called pre-Cambrian simply because they correspond petrographically with rocks which are known to be pre-Cambrian.

It is hardly conceivable that normal Cambrian or Silurian sediments could be deposited in one place on the earth's surface while at the same time crystalline rocks were directly formed in another. The conditions necessary for the development of primary crystalline schists are so different from those of normal sedimentation, that the simultaneous formation of the two seems impossible. One must assume, therefore, as geologists generally do, that the two groups are of different ages, and all the crystalline schists are Archean or pre-Cambrian; or that the crystalline schists were originally true sediments which developed a crystalline texture subsequent to their deposition, by some process independent of sedimentation. The "younger" crystalline schists definitely show that such metamorphism may take place, and their similarity to true Archean rocks suggested the possibility that these older crystalline schists

were produced by some widespread alteration process. In this way the theory of general or regional metamorphism originated.

Theories of Regional Metamorphism.—*Regional metamorphism*, as opposed to contact-metamorphism which is distinctly a local phenomenon, has been regarded as due to alteration processes which have a very extensive zone of action. All theories of regional metamorphism proceed from the conviction that the crystalline schists generally do not possess the characteristics of primary formations. If, therefore, these rocks did not originate from a primitive crust and the oldest chemical sediments, they undoubtedly correspond to sediments and igneous rocks which

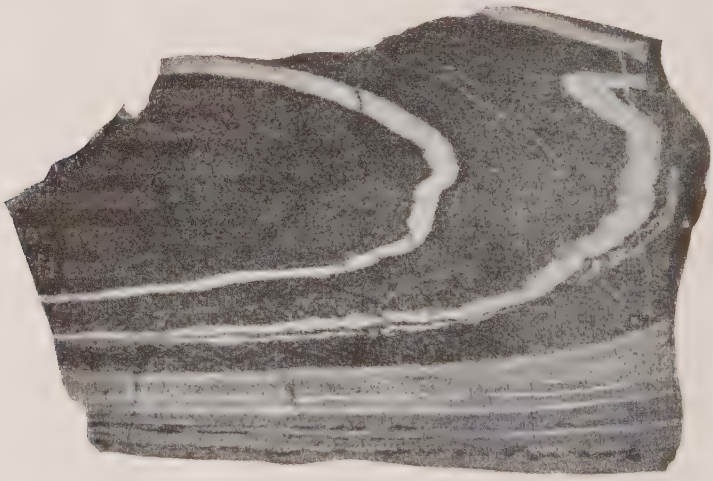

FIG. 97.—Injection schist. Freiberg, Saxony.

occur in an unaltered condition on other parts of the earth's surface. The chemical composition of these altered rocks indicates the character of the original material; simple recrystallization does not produce great chemical alterations, and there is a characteristic chemical difference between clastic and igneous rocks, as was shown in Sections V and VI.

The crystalline schists have been classified, for example by Rosenbusch, on the basis of their chemical compositions. To such a classification the objection has been made that, owing to the great variation in the character of sediments, an arkose or greywacke may somewhere occur which corresponds closely to granite in chemical composition. While this is possible it is very improbable, and the chances are very slight that a gneiss of granitic composition was originally such a greywacke. On the other hand, the igneous rocks may have undergone extensive alteration before metamorphism, and thus a further disturbing factor is introduced. Such alteration

doubtless occurred in many cases, but the results of normal weathering would have slight influence on the enormous rock-complexes from which the crystalline schists must have been formed. With rare exceptions, the chemical compositions of the replacement products, which were discussed in Section VIII, differ just as much from the chemical composition of the sediments, as do those of the original igneous rock itself.

The chemical composition of a crystalline schist is always an important aid in the determination of the character of the original rock, and in certain cases it alone is sufficient. In other cases it may be necessary to confirm the determination by means of the geologic mode of occurrence. If the gneiss formation, for example, is examined by these methods, it will be found that two end-members are easily distinguished. The lower part of the series, as a rule, shows the characteristics of true granites, quartz-diorites, etc., while the upper corresponds to greywackes, slates, and the like.

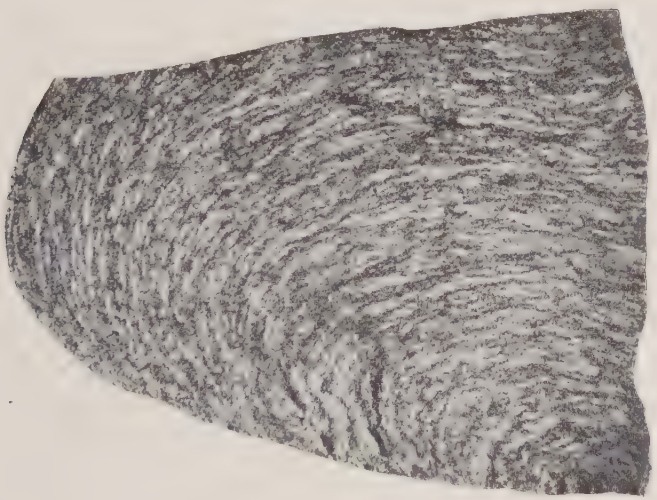

FIG. 98.—Granite made schistose by resorption. Mulda near Freiberg, Saxony.

The latter, also, is distinguished from the former by its much more abrupt variation in habit and composition.

According to their mode of origin, these rocks are called igneous gneisses or sedimentary gneisses, or, following Rosenbusch, *orthogneisses* or *paragneisses*. Between the two, however, there is a third equally justifiable group which possesses the chemical characteristics of neither igneous nor sedimentary rocks. Rosenbusch classified them as *metagneisses*. Certain of these rocks usually show rather perfect schistosity and banding and, like the paragneisses, vary abruptly in composition. These rocks are in part schists injected with granitic magma (Fig. 97), in which the phenomenon of injection can be still distinctly recognized megascopically and microscopically, in part mixed rocks in which the exfoliated schist was more or less completely resorbed by the granitic magma (Fig. 98).

In many cases the conclusions as to the original character of a crystalline schist, drawn from its chemical analysis, may be confirmed by preserved remnants of the original texture. Thus, large quartz boulders, almost unaltered, may be preserved in metamorphosed rocks, or fragments of fossils may be found. In such cases there can be no question as to the sedimentary origin of the rock. On the other hand, the gneisses

of the central Alps show, besides the usual granitic texture, all the other external characters of intrusive rocks, such as inclusions of the country-rock, apophyses, etc. Within them, also, dikes of chlorite-schist occur, and they may show more or less sharply defined light spots with the outlines of the phenocrysts of the original porphyrite (Cf. Fig. 83). Further, in the uralitic hornblende of the amphibolites there may still be distinct traces of the parallel diallage inclusions, which are so characteristic of gabbro. Thus similar examples could be presented for almost all varieties of crystalline schists, definitely proving that these so-called primitive rocks embraced both igneous rocks and sediments.

An objection, which applies equally well to all theories of regional metamorphism, is that even in the very oldest sediments, namely, the basal conglomerates of the oldest fossiliferous formations, there have been found occasional boulders petrographically resembling crystalline schists. According to the theories of metamorphism, if rounded fragments of mica-schist and phyllites occur in the overlying Cambrian strata, these boulders must have been metamorphosed before the Cambrian rocks were deposited. In other words, the metamorphism must have taken place after the deposition of the upper beds of the phyllite and before the deposition of the lower beds of the Cambrian, in spite of the fact that the two series are connected in many cases by all possible transitions. Such occurrences will be discussed in greater detail at the conclusion of this section.

Three theories of regional metamorphism are of especial importance:

1. *Plutonic* (Pluto, God of the underworld) or *anogenic* (ἄνα, up, γίγνομαι, to be born) metamorphism.

2. *Hydrochemical* (Gr. ὕδωρ, water), *Neptunian* (Neptune, God of the sea), or *katogenic* (Gr. κάτω, down) metamorphism.

3. *Dislocation* (Lat. *dislocare*, to displace) or *dynamometamorphism* (Gr. δύναμις, force).

Plutonic and Hydrochemical Metamorphism.—The theory of plutonic metamorphism, which was proposed by Hutton and geologically applied by Ami Boué and Lyell, is based upon the temperature gradient of the earth, the heat of the interior (or, in the language of Hutton, "the subterranean fire") being responsible for the alteration. If sedimentation, in some locality, increases the thickness of the earth's crust by thousands of meters, it causes the lowest beds to pass gradually into the zone of fusion. Here, with the aid of moisture, recrystallization takes place, and the originally clastic rock is metamorphosed into one which is crystalline. More recently Termier substituted "mineralizers," for "moisture" in this theory; the mineralizers being supposed to pass from the molten magma of the interior into the overlying sediments (cf. page 65). Since the metamorphic agents act from below, the lowest beds are most completely changed. Recent formations are altered in fewer cases than are the older, since they

are more rarely covered by deep sediments. Finally the altered formations again appear on the surface by denudation.

Since the temperature gradient is only about 30° per kilometer and probably decreases with depth, this theory appears absolutely untenable. To produce the required alteration there must have been an increase of many hundred degrees. This would have necessitated the deposition and subsequent removal of sediments many kilometers in depth wherever crystalline schists appear on the surface of the earth.

Contrary to this hypothesis is that of hydrochemical metamorphism, which was placed on a scientific basis primarily by Bischof. In this theory, vadose waters are considered the active agents. They force themselves into the rocks, and becoming saturated with various substances, produce alterations in the different formations. The process is the reverse of weathering, for instead of producing disaggregation of the rocks there is an inner recrystallization, in the place of the development of new hydrous products there is a withdrawal of water, and instead of the leaching of constituents there is an addition of material. Hydrochemical metamorphism never became more than a hypothesis. Not only was it unsupported by observations, but the phenomena of weathering under all conditions are opposed to it.

Latent Plasticity and Fractureless Folding.—Since the theory of dynamometamorphism is now the one most generally accepted by petrographers as well as by geologists, it may be well to enquire into its justification. The theory was proposed by Lossen, and was developed from the petrographic side by Rosenbusch and his pupils, from the geologic side by Heim and Baltzer, and from the physico-chemical side by Becke.

In the process of mountain-building the rocks undergo many alterations, some of the changes being megascopically visible in nearly every disturbed region. Sediments primarily are influenced by these orogenic processes. The beds are greatly folded (Fig. 99), relatively recent rocks may become as compact as older formations, and where there is transverse cleavage it is not uncommon to find mica-like minerals upon the joint-planes. Under the influence of great stresses the rocks no longer act as rigid bodies but acquire a certain degree of plasticity. This enables them, within certain limits, to yield to the pressure and change their form. Heim calls this phenomenon "fractureless folding," and says it occurs wherever rocks are subjected to great and gradual lateral stresses. The vertical load prevents movement in that direction, a movement

which would otherwise rapidly relieve the strain. Heim supposed that under the enormous load of the overlying beds, the rocks reached a potentially plastic condition. This permitted the molecules to equalize the differential stresses by gliding and by displacements, with the result that the rocks were able to adjust themselves to the new conditions without making necessary an internal fracturing of the individual components.

The theory of fractureless folding, which was based upon superficial megascopic observations, was long ago shown by microscopic study to be of very limited application. It is true that a

FIG. 99.—Folded Devonian limestone. Barrandefelsen, Bohemia. (H. Eckert, Prag, Photo.)

certain degree of plasticity is the property of all rocks, and that it is developed best where a slowly-moving force acts upon them under an especially great load. The range of the elastic limits of most rocks, however, is rather narrow, and rocks which megascopically appear to be folded without fractures are usually shown by the microscope to consist of mutually displaced fragments of the various constituents, or of internally fractured and re-cemented minerals.

Many veined gneisses show a remarkable folding. For example, the light bands in Fig. 100 are granite-aplite, and its

constituents, especially quartz, are extremely brittle, yet they show no trace of fracturing even on the most thorough microscopic examination. It was therefore thought that these rocks were examples of perfect fractureless folding. A much more probable explanation of such rocks is that the aplite penetrated the loosened joints of a previously crumpled rock. After the solidification of the aplite and the alteration of the sediment by contact-metamorphism, no folding took place.

The degree to which a rock may be folded without fracturing depends primarily upon its composition and texture. Slates, and in fact all rocks which were built up predominantly of colloids, loose aggregates of readily displaceable minerals, or of flakes of mica-like minerals which may be readily bent, are most plastic. Limestone, under great pressure, may likewise undergo considerable re-formation without

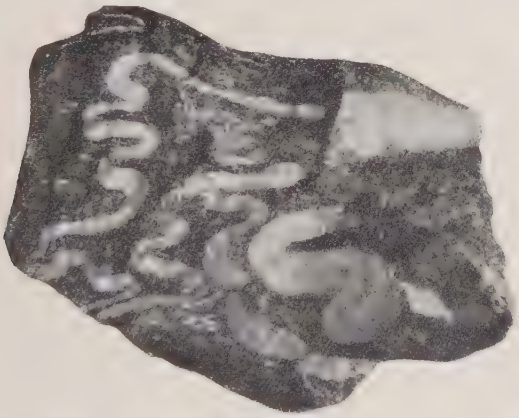

FIG. 100.—Banded gneiss. Untersulzbachtal, Grossvenediger. The contorted aplite veins show sharp contacts against the schist.

breaking. This is probably due to the ability of calcite to form twins (Fig. 4, Pl. VI). Dolomite, however, does not possess the property of gliding, and even under great pressure, mashing only leads to a general fragmentation or endogenic brecciation. This is brought out clearly by weathering, for such rocks disintegrate into a mass of minute, angular fragments of dolomite, the calcareous cement having been dissolved out by the atmospheric agents. The plasticities of feldspar, quartz, and olivine are very slight. The latter two are among the most brittle of the rock-forming minerals, for they break upon the slightest orogenic movement. Thus the degree of internal fracturing, shown by the cataclastic texture, serves as a measure of the pressure.

Rocks composed of several minerals may act quite differently under pressure, owing to their textural differences. Thus, a sandstone, composed of quartz grains surrounded by a clay-like cement, may be considerably folded without being fractured internally, while the constituents of a granite, under the same conditions, would be completely mashed. A very plastic rock, interbedded with one which consists predominantly of brittle minerals, will be folded without breaking; the enclosing brittle rock, however, will be crushed, and into its open fractures the plastic mineral of the former rock will be forced. An example of this is the diabase dike in Fig. 101. This

has been broken up and now occurs in disconnected lens-like masses separated by the plastic enclosing limestone. Similarly, where limestones and brittle rocks are folded together, the former are forced in dike-like, pseudo-igneous forms across the schistosity and into fissures radiating from the crests and troughs of the folds of the brittle rock.

The plasticity of many minerals is considerably increased by heat, especially

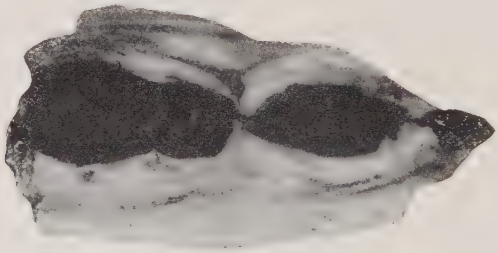

FIG. 101.—Broken diabase dike in marble. Wunsiedel, Fichtelgebirge.

when accompanied by gases and vapors, even though the temperature remains below that at which they soften. This has been shown in a remarkable manner by experiments on limestones and marbles. The fractureless deformation of calcite grains in contact-metamorphosed rocks is thus accounted for.

Such a fractureless bending, however, cannot be produced experimentally in the feldspars, quartz, or other important rock-forming minerals. Their elastic limits are reached as quickly under the conditions of contact-metamorphism as under dynamometamorphism, and instead of being folded without fractures, they are internally shattered. A granite, for example, even under the most favorable conditions, shows no evidence of having become plastic, and there is no adjustment of its borders to that of the country-rock, nor is it ever forced, in the solidified state, into fissures or joints of the country-rock. This artificial hypotheses of plasticity has resulted in the misinterpretation of normal phenomena of igneous sheets in every case where the field distortion of granite or gneiss has been explained as due to a softening of the rock.

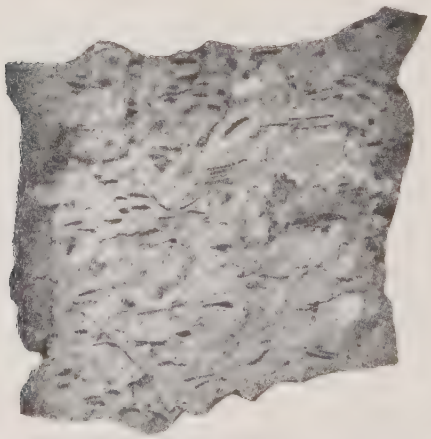

FIG. 102.—Tad-pole-quartz-porphyry. Thale, Thüringen. (Prof. Dr. Klemm, photo.)

An alteration in form without complete fracturing is no more possible for the quartz phenocrysts in certain quartz-porphyries and the quartz grains in certain sandstones, even under the action of pressure or tension, than it is for the same minerals in thousands of other cases where they have shown themselves to be brittle, and not plastically deformable. The stretched quartzes in the quartz-porphyry of Thale in Thüringen (Fig. 102), called Kaulquappenquarze (tad-pole quartz) from their form, and the elongated quartz grains in certain "stretched" sandstones, both of them explained as due to plastic deformation, are doubtless simply primary forms in the

case of the porphyry, and recrystallizations by contact-metamorphism under strong lateral pressure in the sandstones.

Dynamometamorphism.—Heim's view that rocks possess latent plasticity when under the weight of overlying strata, is modified by believers in the theory of dynamometamorphism only by the assumption that the overlying load produces in the solid rock a certain mobility of molecules which permits them to react upon each other and finally leads to a complete molecular re-arrangement. Whether moisture or the heat set free by mechanical re-adjustments aids these chemical reactions is immaterial, the main factor in producing the mobility is undoubtedly pressure.

The theory of dynamometamorphism is based upon the facts that the crystalline schists, in many cases, show the effects of exceptionally great earth-movements, and that the crystallinity of a sediment or the schistosity of an igneous rock increases more and more with the amount of disturbance. In innumerable cases the amount of compression has been estimated solely from the degree of crystalline schistosity of the rock itself; the molecular re-arrangement, supposed to originate in pressure, being at the same time the only evidence that such pressure was especially active. The theory, therefore, *is presupposed to be correct to furnish evidence that it is correct.*

The experimental work of Spring is generally thought to support the theory of dynamometamorphism. He found that a dry mixture of flowers of sulphur and copper shavings could be transformed, under a pressure of several thousand atmospheres and without increasing the temperature, to black crystalline chalcocite. The fundamental basis of dynamometamorphism is the possibility of a molecular re-arrangement in the solid state. That this occurs must be granted, not only from Spring's experiments but from later ones made with various substances, especially with metallic salts. Spring's experiment, however, loses much of its convincing power when the results obtained with rock-making materials are examined, for under pressure as great as 20,000 atmospheres, pulverized lime-carbonate, silicic acid, etc., presented no traces of alteration. Experiments show, therefore, that while the mobility of the molecules of certain substances is great enough to permit recrystallization under the stresses which may exist during orogenic movements, the degree of this mobility varies greatly. In the minerals forming the crystalline schists especially, it is so slight that it seems hardly sufficient to account for a molecular re-arrangement of the rock, even when enormous loads and long periods of time are assumed.

The results of Spring's experiment are those to be expected theoretically; many of the metals, metallic sulphides, etc., are of less volume when fluid than when solid; the silicates, on the other hand, expand on melting. In the first case an increase in pressure must produce a lowering of the melting point, in the second the reverse is true.

Experiments have recently been made in regard to the plasticity of minerals and rocks, more especially of calcite and marble. The results show that while great pressure can alter the form of the minerals, it cannot do so without at the same time

completely mashing them. It is true that these masses develop a certain coherence, but it is only such as any powder will take on when greatly compressed. Recrystallization only occurs under this great pressure when at the same time the thoroughly moistened material is heated several hundered degrees.

Riecke undertook certain experiments to determine the cause for the molecular re-arrangement and the extensive schistosity of metamorphosed rocks. He found, in a saturated solution, that pressure increased the solubility of a crystal in the direction of the pressure, and decreased it at right angles to this direction. *Riecke's principle* was applied by Becke to the dynamometamorphic alteration of crystalline schists. He regarded the ground-water, which circulates in all the pores of the rocks, as a concentrated solution of all the rock-constituents. Lateral orogenic pressure, decreasing the solubility of the constituents in the direction at right angles to it, caused them to grow in this direction, which usually also corresponds to that of the schistosity of the rocks. The circulating water continually brings in new material for this growth by dissolving the constituents on the sides from which the pressure comes.

The importance of the ground-water as a factor in the alteration of rocks diminishes rapidly with the depth. The decrease in the water content of rocks on account of the overlying load, and the dust-dry condition of the walls in fairly deep mines, makes it seem probable that water exists only in the theory. Even if present, the ground-water can be of only slight importance as a solvent for the difficultly soluble constituents of the silicate rocks. Assuming that the solubility of these constituents does increase with an increase in temperature, it is hardly probable, on account of the slowness of the mountain-forming movements and in spite of the poor heat-conductivity of rocks, that there would be enough heat generated by the friction of the particles during the re-formation of the rocks to cause solution.

The development of considerable heat over wide areas, even though the mountain-folding took place relatively rapidly, is purely hypothetical. The fact that the fragmental material occurring in regions characterized by the greatest faulting and even thrust faulting, shows no suggestion of a temperature increase such as would lead to molecular re-arrangements, is strong evidence against this theory. The crushed condition of the rocks and the magnitude of many of the faults show that there must have been great friction, consequently local molecular re-arrangements might well be expected, but are nowhere found, in the normal friction-breccias, or so-called *mylonites*.

Further, in numerous cases sediments have been squeezed and intensely folded without showing a trace of crystalline alteration. The Tertiary deposits of the Glarner Alps, for example, are deformed to a degree rarely found even in the crystalline schists, but while they possess transverse schistosity, they show no trace of crystallinity. The Lochseite limestones also show the effects of very great mechanical movements, but while they have been actually kneaded together (Fig. 103), their character is absolutely different from that of the limestones of the crystalline schists. No trace of newly formed minerals or of recrystallizations due to great pressure appears, not even microscopically.

On the other hand, the Carboniferous phyllites of the Low Tauern contain fragments of rocks which show no traces of mechanical strains. They contain plant remains which show no signs of corrosion and graphite which still preserves the structure of the coal from which it was derived, yet the schists themselves are entirely crystalline in texture. Further, in many places in the Alps, as in the Stubai group, Monte Rosa, etc., highly crystalline, altered sediments occur in practically undisturbed and nearly horizontal beds. The same is true of the recent, crystalline schists of Attica. The general term dynamometamorphism, therefore, does not correctly indicate the actual phenomena.

The theory of dynamometamorphism was chiefly developed in the western Alps, where it was based, primarily, upon assumptions which are demonstrably false. The gneiss-like character of the central Alpine granites misled geologists, and caused them to classify the rocks as gneisses. Further, the sedimentary aspect of the granites, and the belief that all crystalline schists were Archean, gave rise to the belief that they are of great age.

FIG. 103.—Limestone with kneaded structure. Lochseite near Schwanden, Switzerland.

The gneisses of the Alps occur in contact with a great variety of rocks belonging to relatively recent formations, from Carboniferous to Jurassic, as shown by their petrographic character or their fossils. In some cases several superposed beds of gneiss occur in the sediments, in others the latter are cut by the gneiss. Further, fragments of the sediments occur in the gneiss, and fragments of the gneiss in altered sediments. All this is shown in Fig. 104, which represents one of the best-known occurrences, the contact of gneiss and limestone in the Bernese Oberland. If the gneiss is Archean, it is much older than the overlying and interbedded sediments, consequently its position can be explained only by assuming that great displacements, faults, and folds have brought these rocks to their present positions. Believers in the theory of dynamometamorphism found in these hypothetical movements the cause for the alterations in the rocks, but it is much more probable that they are due exclusively to contact-metamorphism.

Even after petrographic investigations showed that there could be no question as to the original granitic character of these rocks, the idea of great age still clung to them, and was expressed in the name *protogine*. The contact between the granite and the schist was supposed to have been caused by later displacements. The granite was thought to have possessed originally a normal, haphazard texture, but under the stresses of faulting and folding to have developed such new minerals as occupy the smallest possible molecular volumes, for example, clinozoisite and garnet. At the same time, the originally unoriented mica flakes arranged themselves at right angles to the direction of the pressure.

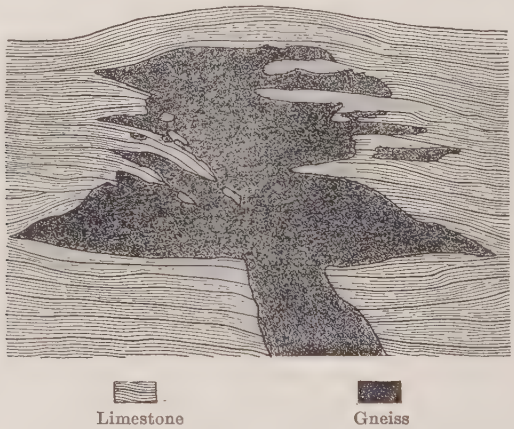

FIG. 104.—Contact of gneiss and limestone in the Bernese Oberland.

Great quantities of anomalous minerals occur in these rocks as irregularly distributed inclusions in the plagioclase crystals. The latter are usually absolutely fresh, and if the mica flakes rotated within them, it is necessary to assume that the plagioclase was in a viscous condition. As a result, believers in the theory of dynamometamorphism found it necessary to postulate that the originally haphazard-textured, normal granite, which crystallized from the melt, was reduced by later orogenic forces to a condition very similar to that of the original magma, and that out of this mass it crystallized for the second time, but now as gneiss.

According to this theory of secondary schistosity of the granite, the metamorphism of the sedimentary rocks which overlay them proceeded under the same conditions. Since the granite was assumed to be of greater geologic age, the sediments must have

been deposited later upon the previously eroded granite, or have been folded into or thrust over it.

That the central gneiss has broken through its schist-shell in numerous cases, that magmatic differentiation is shown by aplitic and lamprophyric phases in the border zones, and that the aplitic dikes succeeding the granitic intrusion cut not only the granite massif itself but also the schistose mantle to a distance of many kilometers, all these were disregarded by believers in this theory, or at most were used by them as bases for constructing artificial faults and folds, which were then offered as further proofs of dynamometamorphism.

That no typical contact-minerals, such as are always present elsewhere in contact-zones, occur in the mica-schists or the limestones of the Alpine region has been cited again and again as strong evidence against the theory that the schistose crystalline border of the granite is due to contact-metamorphism. This objection is easily met, and reference need only be made to the section on piezo-contact-metamorphism, where various views are brought together.

Facies of the Crystalline Schists.—If all the rocks which have been called crystalline schists in different regions are examined more closely, two end-members connected by various transitions may be recognized. It is to be emphasized, however, that these transition rocks do not unite the two extremes in one and the same area, but that the end-members are always sharply separated.

In almost every occurrence it is possible to distinguish three varieties of "crystalline schists."

1. Igneous rocks of normal composition which show schlieren or a schistose development. These are called *ortho*-rocks.

2. Metamorphosed rocks, best grouped together as metamorphic schists or *para*-rocks.

3. A combination of both rocks. In these the metamorphic schists are saturated with the igneous rock. They are injection-schists or migmatites, and may be called *meta*-rocks.

With these subdivisions in mind, an examination of the parallel-textured, unaltered, igneous rocks of the intermediate Alps shows them to be chiefly granites whose composition and structure have been somewhat modified by inclusion of schistose rocks. In the corresponding rocks of the central Alps, and in the cores of folded mountain ranges in general, the parallel structure appears to be the result of piezocrystallization, and these rocks clearly show the action of pressure in their structure and mineralogic composition. In general, therefore, a distinction can be made between a normal and an Alpine facies, the end-members being quite distinct.

Further, it is significant that corresponding to, and connected with, these contrasting facies of gneiss, there are also contrasting

facies of metamorphosed schists. The Alpine facies of the schist show piezo-contact-metamorphism, while that which occurs with the normal gneiss has more or less the composition of a normal contact-rock. In other areas the gneiss as well as the metamorphosed schist is of intermediate character.

On the theory of dynamometamorphism, these different facies are explained as phenomena of alteration dependent upon depth. Three zones are differentiated.

1. The upper zone, under relatively low temperature and little hydrostatic pressure, on account of the comparatively slight weight of the overlying strata, but under great lateral pressure from the action of orogenic forces. In this zone the re-formation is predominantly mechanical, and few new minerals are formed; those that do appear are hydroxyl-rich and of minimum volume. The syllable *epi* (Gr. ἐπί, above) is prefixed to the names of the rocks occurring here, for example, epi-greenstone-schists, epi-quartzites, etc. They correspond to the rocks occurring in the outer piezo-contact-metamorphic zone.

2. An intermediate zone under higher temperature. Mechanical textures are less common, and complete recrystallization takes place with the formation of heavier and less hydrous minerals. Rocks supposed to have originated here receive the prefix *meso-* (Gr. μέσος, in the middle), for example, meso-mica-schist, mesomarble, etc., and correspond chiefly to the rocks of the inner zone of piezo-contact-metamorphism.

3. The deepest zone, in which high temperature is of greatest importance. Here the prefix *kata-* (Gr. κάτω, below) is used, as in katagneiss, kataamphibolite, etc. These rocks, in general, correspond to normal contact-rocks, and to their injected and resorbed varieties.

Perhaps there would be a certain justification for this scheme of classification if it were possible somewhere, or in some manner, to determine the depth within the earth's crust at which the metamorphism took place. As it is, the depth is determined solely by characteristics which geologists think the rocks from such depths should show.

These divisions would be acceptable if the different zones, or at least the last two, could somewhere be found in place, one above the other. At present the rocks have never been found together, the meso- and kata-rocks being everywhere separated geologically, and usually geographically. Although the meso-rocks definitely occupy an intermediate position petrographically, this does not mean that in any region they actually represent transition members between the two extremes. It is not a difference in depth which has produced the difference between these rocks, and just as little are dynamic processes the chief cause of their metamorphism. The variation is due, with much greater probability, to different physical conditions, such as were contrasted above, namely, piezocrystallization and piezo-contact-metamorphism of normally crystallized melts on the one hand, and normal contact-metamorphism on the other. The processes of regional metamorphism, which are apparently so extensive, greatly resemble in their essentials those of simple contact-metamorphism.

Summary.—A broad view of all dynamometamorphism, at least in the upper and middle zones, may be obtained by examples from the central Alps. The central Alpine gneisses (central gneiss, protogine, etc.) are chiefly granitic rocks which differ from normal granites in containing certain accessory constituents, and by certain

peculiarities of structure. They occur in contact with a schistose mantle of Carboniferous or Jurassic age, as shown in a few cases by fossils. The border zone is composed of rocks which are very different in different parts of the Alps but which possess the common characteristic that normal contact-minerals are more or less completely wanting. The relationships between the igneous rock and the surrounding schist-zone, however, are such that they can be explained only on the basis of a primary igneous and not a secondary mechanical contact. In other words, these gneiss-like granites solidified within the schistose shell in which they now occur. They are not Archean, but clearly younger than the surrounding sediments into which they were forced in a molten condition.

The cause for the enormous flows which must have occurred in the whole central chain of the Alps in relatively recent geologic periods probably can be found in considerable faulting during the period of especially great folding. During such orogenic movements the rocks were completely shattered, thereby making easy paths for the melt in its movement upwards. The magma finally crystallized under great stress. At the same time, the mineralizers which emanated from the magma saturated the shaken country-rock to unusual distances and, on account of the exceptionally high pressure, produced molecular re-arrangements which led to the formation of rare mineral combinations.

This view offers an explanation for the various geologic modes of occurrence of the central Alpine gneisses, and for their petrographic characteristics; why gneiss-like granites occur almost everywhere with the schists, and why the crystallinity of the schists generally decreases with distance from the gneiss. It is especailly noteworthy that in the Low Tauern the rocks farthest from the central granite are very much more faulted than those nearer to it, yet they are much less crystalline. Further, some of the crystalline chloritized schists which directly overlie the central granite contain remarkably well-preserved plant remains. The common slates, however, a little farther away, are intensely folded, faulted, and in many cases transversely schistose, and while their sedimentary character has not been altered by molecular re-arrangement, their fossil plants appear only in indistinct traces.

Even according to Rosenbusch, the textures of sediments altered by dynamometamorphism cannot be distinguished from the textures of contact-rocks. In both, the minerals become filled with inclusions arranged parallel to the original schistosity, and the coarser clastic material and the sharp boundaries between the different beds appear as clearly in the one as in the other. Furthermore, at the contact between the central granite and the limestone there are developed transition members analogous to those found along normal igneous contacts against limestone, for example at Monzoni, Christiania, etc. Again, tourmaline appears everywhere as a metasomatic mineral in the rocks of the schist zone of the central Alps, and its long, needle-like crystals, in many cases embedded at right angles to the schistosity, show the same bands of inclusions as do the remaining constituents. It is very noteworthy that in many rocks of the schist-zone, even in those which externally appear intensely folded, no trace of mechanical deformation appears; the mica flakes are not bent nor the tourmaline cyrstals broken. To explain the peculiar phenomenon that minerals which originated by orogenic processes show no traces of deformation by these forces, Rosen-

busch formulated the law that no mineral can be destroyed by the force which formed it. Since it is inconceivable that a crystal which originated through dynamometamorphism should behave in a different manner under pressure from another crystal of the same substance but formed under different conditions, this law should be discarded as unjustifiable.

Little is to be gained by giving special names to the textures produced by dynamometamorphism. If the larger porphyritic crystals of such rocks, usually with irregular outlines and corresponding to the "knots" of normal contact-rocks, are called *porphyroblasts* (Gr. $\beta\lambda\alpha\sigma\tau\grave{o}s$, sprout), it no more suggests their special chemico-geological significance than if the normal mosaic texture of contact-rocks, which is also found everywhere in the crystalline schists, is called *granoblastic*. The appearances are identical whatever the names, and this was clearly recognized by Rosenbusch himself, the most prominent among the founders of dynamometamorphism.

Granite and the Crystalline Schists.—Taken all in all, the geologic as well as the petrographic attributes of the crystalline schists of the central Alps indicate an intimate connection between the igneous origin of the central granite and the contact-metamorphism of the country-rocks. In consequence of the general shattering of the rocks by orogenic movements, the metamorphic contact-zone may be traced to unusually great distances from the central massif, in many cases to double the normal distance. In many places at these great distances, definite proof of igneous activity is offered by the occurrence of aplite dikes. It would have been impossible for the aplite to have developed a holocrystalline texture except where the country-rocks themselves were still warm enough to permit the slow cooling of the intruded material.

The action of great pressure is very distinctly shown by the condition of the various crystalline schists of the Alps, and it is primarily in the relations between these rocks and those which are undoubtedly igneous that the causes for their abnormalities are to be looked for. The orogenic processes shattered the rock and the magma of the deeps was forced into the loosened strata, there to undergo, because of continuing stresses, the numerous modifications which are included under the name of piezocrystallization.

The gneiss-like appearance and the abnormal accessory constituents of these granites, therefore, become primary properties. Judging from their similarity—chemical, mineralogical, and structural—these rocks appear to be of about the same geologic age in the whole chain of the Alps, and this, certainly, relatively recent. As was shown above, the contact-metamorphism of the country-rock did not begin until the granite was in the last stages of its

solidification. The great stresses which still existed everywhere within the disturbed region are shown in the anomalous minerals of the piezo-contact-metamorphism; that the usual mechanical textures do not everywhere appear is due to the fact that the movements of the crust, for the most part, came to a standstill with the solidification of the great granite mass. Entirely analogous phenomena may be observed in all other greatly-folded regions, and everywhere piezocrystallization and piezo-contact-metamorphism go hand in hand.

The character of the crystalline schists in undisturbed regions is extremely variable, and only exceptionally can piezocrystallization be recognized. Where this is the case, a more or less perfect parallelism of the mica flakes, due to the formation of schlieren in the border zone where schistose material was assimilated, can be observed in rocks which in texture and otherwise are normal granites. By no effort of the imagination can these rocks be regarded as having been formed by dynamometamorphism, since they show no trace of a cataclastic texture. Neither are the much-folded cordierite-gneisses of the Bavarian Forest dynamometamorphosed, but they are built up of parallel bands of rocks of the most different types. Bands of cordierite-hornfels, the most normal of contact-rocks, alternate with granite-aplite. The latter are of considerable size in the troughs and crests of the folded schist, and in many cases cut it transversely, yet the constituents of these rocks and of the hornfels show neither internal bending nor fracturing. As a matter of fact, the cordierite-gneisses of the Bavarian Forest are normal injection-schists, with no traces of mechanical action, in contact with normal granitic rocks.

FIG. 105.—The gneiss region of the inner Bavarian Forest.

The thickness of the crystalline schists in different regions is very variable, the maximum estimate being 50 to 60 km. A critical examination of the different areas shows that instead of forming a geologic unit, the schist is actually composed of many different members. The sketch map in Fig. 105 shows a part of the so-called Her-

cynian gneiss formation of the Bavarian Forest. Taking into consideration the dip of the strata, the thickness is about 12 to 15 km. A cross-section through the region, for example near Zweisel, shows at least ten large and innumerable smaller areas of true haphazard granite, in all certainly amounting to more than 5 km. These 5 km. must therefore be subtracted from the total thickness of the complex. Further, the large granite masses show that a great granite massif is present beneath the whole region, the insignificant portions laid bare by erosion being simply apophyses from it. The granite not only occurs in these larger masses but it is injected into the schists everywhere in the region. This shows that the 15-km.-wide altered zone is only seemingly the extent of the metamorphism, the sedimentary rocks themselves actually being in much more intimate contact with the granite than is apparent at the surface. Toward the north, near Eisenstein, the granite impregnation ends, and only isolated patches of granite are found. The rock here is mica-schist, while still farther distant it is phyllite. As the distance from the igneous rock increases, the folding and crumpling of the schist decreases, the so-called phyllites showing only very fine crinkling.

If the rocks which have been altered by contact-metamorphism, and this includes most of the gneiss, be subtracted from the enormously thick crystalline schist-formation, there will remain but a small portion of the rocks to be included in the estimate of thickness. It must be remembered, also, that where narrow, uniform dikelets of igneous rocks intersect a region, they can only be apophyses of larger masses lying underneath. With these facts in view, the distinction between contact- and regional-metamorphism, which always has been emphasized in geologic literature, loses much of its significance, and it becomes still less important when it is noted that the most characteristic rocks of contact-zones, such as "knoten-," "garben-," and chiastolite-schists, also occur in the crystalline schist area. The identical textures and mineralogic compositions of innumerable crystalline schists and contact-rocks show the analogy between the alteration processes by which they were formed. If all the gneisses which have been shown by modern petrographic methods to be of igneous origin, and all those rocks which can be recognized as true injection schists, and finally all rocks which are demonstrably due to contact-metamorphism were separated from the crystalline schist formation, it would be much easier to grasp the meaning of the chemico-geologic processes which produced them than now when all these different varieties of rocks are dragged along as useless ballast.

Viewed from the standpoint of Stübel's theory of vulcanism, the following conclusions are reached. The original crust and the oldest sediments can never be examined, for they were repeatedly broken up by volcanic action, covered by igneous material, were resorbed, or lie buried at such depths that the deepest borings or mines cannot

reach them. An examination of the sediments and the fossils from the Cambrian to the present shows that the crystalline schists are not especially old. Variations in climate had already been established in the oldest geologic periods, and the interior heat had, at most, only a very slight effect upon conditions on the surface; that is, the crust at that time had already attained a considerable thickness. Long periods with conditions favorable for the existence of organisms preceded the Cambrian, at which time the climatic conditions upon the earth were nearly the same as those which exist at the present time.

The struggle between igneous and sedimentary formations had been going on for many long geologic periods before the deposition of the oldest sedimentaries now known. The deep deposits which had been laid down upon the first solid crust of the earth had been completely broken up, and impregnated and altered by the igneous rocks, and from their fragments new beds were formed. The enormous igneous intrusions of the past probably altered the sediments very much more extensively, but in a manner analogous to, that in which the later rocks were altered. There are thus found, in the oldest clastic deposits, fragments of much older formations which have the characteristics of the crystalline schists.

No certain proof exists that the crystalline schist boulders which occur in sedimentary rocks were derived from directly underlying crystalline schists, nor that they were already crystalline at the time of the formation of the sediments. For example, from boulders of gneiss in certain altered sediments of the central Alps, the conclusion has been drawn, without any attempt to establish the identity of the two kinds of gneiss petrographically, that the sediments were deposited upon the gneiss-like granite after its intrusion. The sediments were undoubtedly deposited upon some kind of a foundation, and it is probable that this foundation was composed, in part at least, of gneiss-like rocks. It cannot be questioned, however, that the gneiss-like granite is younger than the schist which it has penetrated and lifted. While rocks having the chemical compositions of argillites and sandstones indicate the previous weathering and denudation of a region of granite or gneiss just as clearly as do included boulders, yet one is not justified in concluding from the occurrence of sandstone or arkose in the beds overlying a granite that they were formed from the weathering of the latter.

In conclusion, the results of these observations may be summarized as follows:

1. The crystalline schist formation is not a formation in a geologic sense, for certain more recent rocks have all the petrographic characters of the crystalline schists. Their petrographic similarity, which is the only reason for placing them all in the so-called Archean, can not be used, therefore, to determine their geologic age. The rocks which at the present time are classed as older or true crystalline schists, and are placed in the Archean formation, may be of any geologic age; the only property common to all being the fact that, as yet, no fossils have been found in them, the younger crystalline schists differing from them only in this respect.

2. The crystalline schist formation is not a formation in a petrographic sense, its rocks having different modes of origin.

They are in part sediments, in part igneous rocks; some are primary, some are metamorphosed.

3. The so-called crystalline schists are not necessarily metamorphic rocks, for some of them have not been metamorphosed.

4. Many extensive areas of crystalline schists are made up of igneous and contact-metamorphosed rocks of very different geologic ages. Instead of calling the different members mica-schist, etc., names which give false impressions as to their ages, they should be designated by proper descriptive names. Only after being thus separated will it be possible to determine the genetic relationships of true crystalline schists.

5. Dynamic disturbances primarily produce brecciation of the constituents of a rock. Whether they may give rise also to molecular re-arrangements cannot be determined definitely. Most of our knowledge at the present time seems to indicate the contrary.

6. The theory of dynamometamorphism can no more withstand a critical examination than can the theories of the formation of primary crystalline schists, diagenesis, or plutonic or hydrochemical regional metamorphism.

7. The oldest known fossiliferous sediments were formed under conditions which differed at most but very slightly from those existing at the present time. From the first formation of the earth to the deposition of the Cambrian, therefore, much more time must have elapsed than is generally allowed by geologists. The Cambrian must have been preceded by long periods of sedimentation, but no more traces of these deposits have been found than of the still older chemical precipitates from the hot, primordial universal sea.

X. JOINTING AND TEXTURES

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Appearance of Surface Exposures of Various Rocks.—The general character of the surface exposures of any type of rock depends primarily upon its jointing and its texture. A rock mass is usually divided into separate parts by joint-planes which may be open or, in fresh rocks, hardly visible. Entering the rock along these joints, the agents of weathering proceed to destroy it, the amount and rapidity of the destruction depending primarily upon the texture of the rock and the number of joints.

The relief of the surface is not produced exclusively by these factors, however, for the various climatic zones of weathering are of great importance, and one and the same rock may assume quite a different appearance in a different zone. Granular igneous rocks, which undergo chemical weathering relatively easily and are converted into grush by partial solution, show soft, rounded outlines with gentle slopes in regions in which chemical weathering predominates. This is the normal mode of occurrence of granite in moist temperate or warm climates (Fig. 106). But the same rock takes on an entirely different form in arid regions. Here in

many cases it is exposed in vertical walls (Fig. 107), and presents a very impressive appearance. There is a similar difference

FIG. 106.—Rounded exposures of granite with a rock-sea in the foreground. Grosse Schneegrube, Riesengebirge. (H. Eckert, Prag, Photo.)

between argillites, sandstones, etc. under these conditions, for while they disintegrate readily in humid regions and rarely out-

FIG. 107.—Granite walls, Mount Sinai. (After v. Lendenfeld.)

crop, in arid regions they stand out in most grotesque shapes as hoodoos, buttes (Fig. 51), and other bad-land forms.

Rocks which have no regular joint-planes but are quite compact, especially serpentine (Fig. 108), reef-limestones and dolomites (Fig. 55), quartz-dikes (Fig. 56), etc. tend under all conditions to stand out in distinct relief from their surroundings.

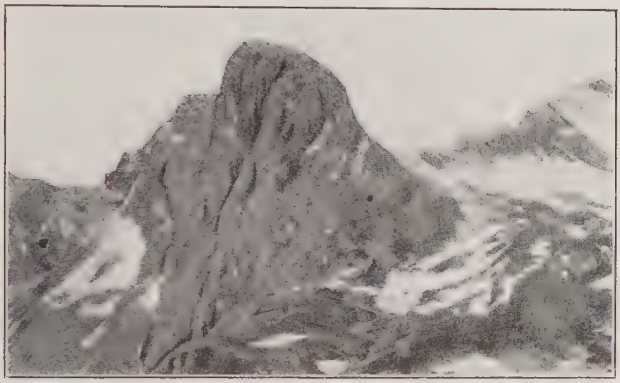

FIG. 108.—Serpentine stock. Goslerwand, Gross Venedig province.

But it is not alone the firmly-cemented and jointless rocks which appear in steep cliffs; these forms are just as characteristic in massive deposits of loose, fine-grained materials which weather readily.

FIG. 109.—Trass deposits in the Brohltal near Andernach on the Rhine.

Examples may be found in the cliffs of the Appenines, along the chalk shores of the Baltic and North Seas, in the trass deposits in the Brohl Valley (Fig. 109), and in the loess deposits of central

Asia. Just as characteristic are the so-called earth pillars or hoodoos (Fig. 63) which are found in many porous glacial deposits, talus slopes, and volcanic tuffs.

If the characteristic forms of rocks which possess distinct jointing are examined, it will be seen that there is a close relationship between these forms and the forms of the mountains themselves. Where normal granites have approximately horizontal joint-planes, they appear in the usual rounded exposures, but where the schistosity is good and is at a high angle, the rock appears in sharp ridges and ragged peaks (Fig. 110). Various sedimentary rocks,

FIG. 110.—Jagged peaks in schistose granite (protogine). Aiguilles des Charmoz et de Trélaporte. (Wehrli, Zurich, Photo.)

here and there, show similar ragged features when their bedding-planes are steeply inclined. Where the strata are more nearly horizontal the exposures are flat, and the planes may be deeply dissected by canyons (Fig. 53).

Jointing and Parting in Rocks.—The terms *jointing* and *parting* are applied to certain directions in rocks in which they fracture more easily than in others. In this sense joint-planes include the bedding-planes of sedimentary rocks as well as certain fracture-planes, called *rift* and *grain* by quarrymen, of many igneous rocks. The latter lines of weakness, which may be imperceptible to the inexperienced in rocks which are fresh but distinctly visible when

they are weathered (Figs. 6 and 47), permit the removal of rectangular blocks with relatively plane faces from quarries in which the rocks appear to be perfectly massive. The stresses producing joints of this kind were developed by the contraction of the cooling igneous rock. They must have been of extraordinary force at times, for the hardest and least cleavable minerals, such as quartz and olivine, have in some cases been so perfectly and smoothly sheared that the two parts of a crystal may be found in opposite sides of a fissure.

The most common method of separation in igneous rocks is the so-called *platy-parting*, which predominates in persilicic and mediosilicic rocks of the granite, quartz-porphyry, phonolite, and

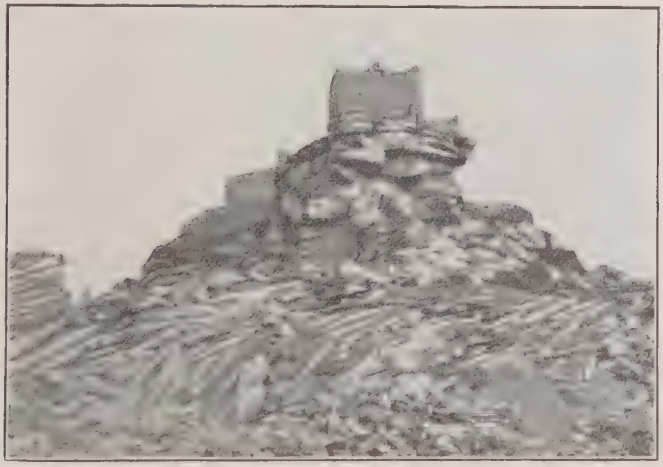

FIG. 111.—Platy-parting of a granite laccolith. Flossenbürg, near Weiden, Oberpfälz.

andesite groups. This parting is generally parallel to the cooling surface; in granite (Fig. 111), for example, it is parallel to the surface of the laccolith, while in extrusive rocks, such as phonolite, it is parallel to the surface of the lava-flow. In vertical dikes, the parting is vertical, and the joints, parallel to the cooling surface, may give rise to gorges with vertical walls, as in the Eggental (Fig. 112).

The behavior of different rocks with platy-parting, when subjected to weathering, is quite different. The plates of fissured granites are only slightly thinner near the surface than farther down, while phonolite, under the name conditions, splits into plates no more than a millimeter in thickness, the so-called *paper-*

porphyry (Fig. 49). Plates of quartz-porphyry generally differ but little, whether fresh or weathered.

FIG. 112.—Platy-parting in quartz-porphyry. Eggental, Bozen.

Second in importance is *columnar jointing*. This occurs primarily in subsilicic extrusive rocks such as trap (Fig. 113),

FIG. 113.—Prismatic parting in trap. Giant's Causeway, Ireland. (After F. Toula.)

melaphyre, and basalt, but it is also found in silicic rocks, for example in the quartz-porphyry from Sigmundskron, near Bozen.

Upon weathering, such columns develop cross-joints, and gradually exfoliate into onion-like spheres (Fig. 48). In other cases oblique

Fig. 114.—Oblique parting in quartz-porphyry. Crest of the Wolfstein, Kosten, Bohemia. (Eckert, Prag, Photo.)

parting-planes cause the rock to break into acute-angled blocks (Fig. 114).

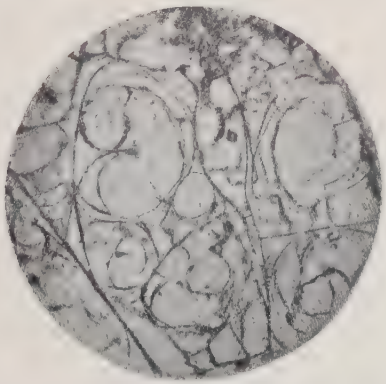

Fig. 115.—Perlitic parting. Perlite. Glashüttental, Schemnitz, Hungary.

Glassy igneous rocks, in many cases, show *spheroidal partings*, varying from the microscopic pearl-like shells in perlite (Fig. 115) to spheres as large as one's fist in kugel-porphyry. These cracks are recognizable even in completely weathered material, while in fresh rocks the parting may be so complete that the rock falls into a grush called *marecanite*. Here and there distinctly crystalline igneous rocks, such as melaphyres, show a coarse spheroidal parting.

Sedimentary rocks may also show a parting independent of the bedding. Thus the parallelopipedal parting of sandstone is caused by two very perfect cleavages at right angles to the bedding. Rocks which are so joined break up, under the influence of weathering, into grotesque columns, such as those which make the scenery of Saxon Switzerland so attractive (Fig. 116).

FIG. 116.—Parallelopipedal parting in sandstone. Adersbach, Bohemia. (H. Eckert, Prag, Photo.)

A great deal of parting is due to secondary orogenic forces. Thus most of the gneiss of the Bavarian Forest is fractured across the schistosity, while certain indistinctly schistose granites of the Oberfalz are so regularly fissured and recemented by secondary biotite that the rock appears to be schistose and banded in two directions (Fig.

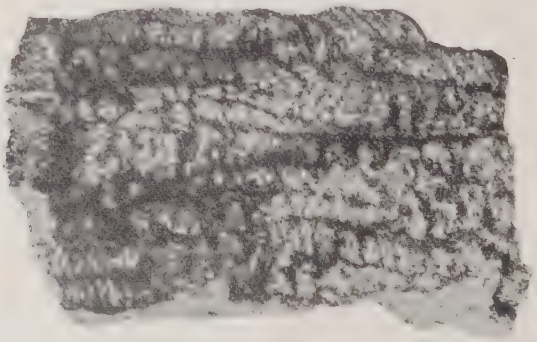

FIG. 117.—Granite. Wondreb, Oberpfalz.

117. In the figure the secondary cleavage, with its biotite-filling, is horizontal). Similar, but much more uniform, is transverse schistosity or rock cleavage. This is developed at right angles to the pressure, and cuts the bedding of sedimentary rocks at an angle. It is generally much smoother and more complete than the bedding-plane itself. Such cleavage is found in many sandstones, but it is especially well

developed in certain argillites (Fig. 118), which become very compact and are then of commercial importance as roofing-slate.

Under the same forces, brittle rocks of uniform texture, such as quartzites or

FIG. 118.—Transverse schistosity cutting across somewhat bent beds of slate. Goslar. (Dr. Baumgärtel, photo.)

dolomites, are crushed to small angular fragments, in many cases quite uniform in size. These are later recemented and form the so-called *endogenic* (Gr. ἔνδον, within) *breccias* (Ital. *breccia*, break) (Fig. 119). If the cement weathers easily, these rocks

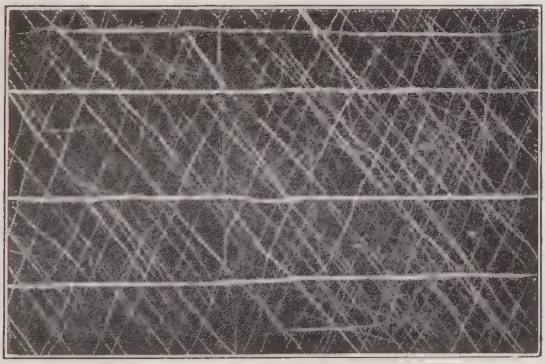

FIG. 119.—Dolomite with parallel systems of veins. Saalburg.

break down into an angular grush, such as is characteristic of numerous Alpine dolomites.

Parting may also be brought about by the heat of contact-metamorphism. This is shown in the columnar parting of fritted sandstones, granites, burnt clays, and coked coals.

Megascopic Characters of Rocks.—The appearance of a rock, that is its habit, depends upon the development and arrangement of its constituents so far as these can be seen megascopically. In certain rocks, called *phanerites* (Gr. φανεὸς, distinct), the chief constituents, and usually their arrangement and development, can be distinctly recognized with the unaided eye or by the aid of a low-power hand-lens. In other rocks the greater part of the constituents cannot be seen without the microscope. Such rocks are megascopically *cryptomerous* (Gr. κρύπτος, hidden) or *aphanitic* (Gr. ἀφανιξομαι, to become invisible).

The constituents of almost all rocks may be recognized by the aid of the microscope, and consequently are microscopic phanerites. In a few cases microscopic examination is of no assistance, but with the development of microscopic methods the number of such rocks is ever decreasing. Such rocks are called *adiagnostic* (Gr. α, not, διάγνωσις, distinguishing).

The degree of cohesion between the individual constituents of a rock is very important, for upon this depends the resistance of the rock to pressure or tension. In crystalline rocks the cohesion depends upon the more or less intimate manner in which the individual minerals are intergrown, in many clastic rocks it is doubtless purely mechanical, the overlying pressure having forced the individual particles so closely together that considerable force is necessary to separate them. The sediments may be divided into three classes, namely unconsolidated, porous, and compact; for example sand, clay, and limestone.

As mentioned above (page 6), rocks may be crystalline or clastic. The former may be subdivided according to the size of the components into *giant*-grained, with constituents ranging in size from a cubic decimeter to several cubic meters, as in the pegmatites, *large*-grained with constituents of the size of a fist, *coarse*-grained with components more than a cubic centimeter in volume, *medium*-grained with individuals of several cubic millimeters, and *fine*-grained with all components less than one cubic millimeter in size. *Dense* rocks, finally, are those which are megascopically cryptomerous. By far the greatest number of crystalline rocks are between medium-grained and dense.

The individual grains of a rock, in most cases, are in very close contact, and the rock appears compact; but rocks without minute cavities are very rare. Fresh granite and basalt, for example, are very compact, yet drops of moisture may appear

upon freshly fractured faces of the most massive basalts, indicating that water had access to the interior. In some cases the individual grains of a rock are less intimately intergrown than in others. An especially good example of this is found in saccharoidal dolomite, whose great porosity is shown by the rapidity with which it will absorb colored solutions. On account of its loose texture it readily disintegrates by atmospheric agents and falls into the so-called dolomite-ash. Granites which are full of little drusy cavities are porous and weather very rapidly. They are called *miarolo* by the Italians.

Rocks containing large angular cavities due to leaching are called *cellular* or *cavernous*. *Scoriaceous* or *vesicular* rocks contain round or elongated cavities produced by the escape of gas from the melt during solidification. *Porous* rocks are those whose cavities are chiefly of microscopic dimensions. *Frothy* rocks, finally, are those made up of a finely divided network of glassy material, for example pumice. When the cavities of any of these rocks are filled with secondary minerals the rocks are called *amygdaloids* (Gr. ἀμύγδαλον, almond).

The constituents of certain rocks have no definite orientation, and the texture is *haphazard* or *random* (Ger. *richtungslos*). In

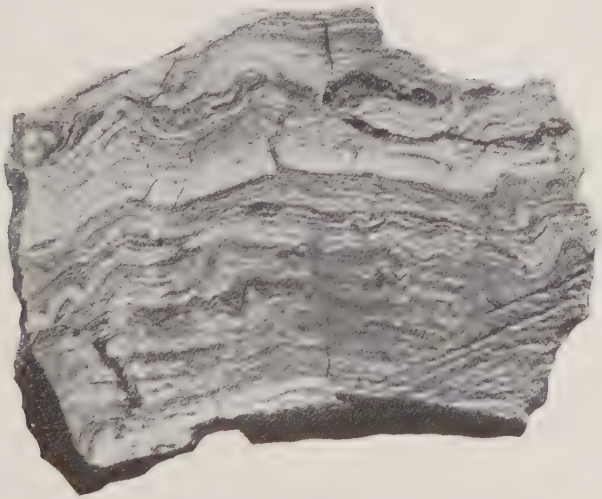

Fig. 120.—Fluidal textured quartz-porphyry. Gross-Umstadt, Odenwald.

other rocks the constituents have a parallel arrangement. Such rocks are *banded* or *laminated*, or, when there is a distinct parting, *schistose*.

The normal texture of igneous rocks is haphazard, but all varieties of parallel textures are to be found as well. Thus in certain gabbros (Fig. 18) a banding which is due to magmatic differentiation shows all the characteristics of normal bedding. A similar appearance is found in many granites with schlieren (for example, Fig. 98), and in consequence they have often been called

gneisses. The latter form of banding is especially well developed in extrusive rocks which are predominantly glassy, and since this texture originated in the flowing movement of the lava it is called *fluidal* (Lat. *fluidus, fluere,* to flow) or *fluctuation* (Lat. *fluctuatio, fluctus,* wave). It is especially distinct in altered rocks, the parallel

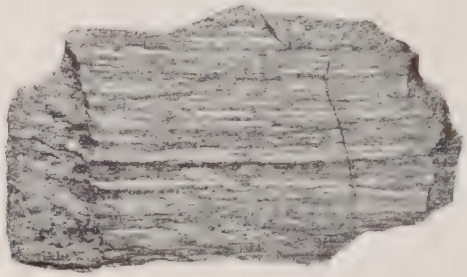

FIG. 121.—Schistose Central granite. Val Antrona, Monte Rosa.

arrangement being brought out by bands of different colors (Fig. 120). Elsewhere layers of bubbles, pores, or devitrification products produce an excellent banding, or it may be caused by parallel tabular crystals. In the latter case a schist-like cleavability is also developed in the rocks.

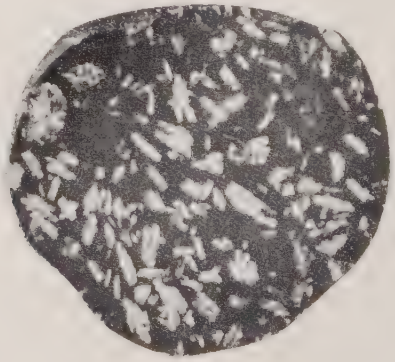

FIG. 122.—Labradorite porphyrite with tabular plagioclase. Elbingerode, Harz.

As already mentioned, igneous magmas may take on a parallel texture under the action of piezocrystallization. This is the cause for the gneiss-like character of the central Alpine granite (Fig. 121). The flaser- and augen-textures associated with piezocrystallization were described in detail on page 56, and it was also mentioned that schistosity may be produced in originally haphazard textured

igneous rocks by contact-metamorphism or by post-volcanic processes during orogenic movements.

In contrast to equigranular rocks are the *porphyritic*, in which

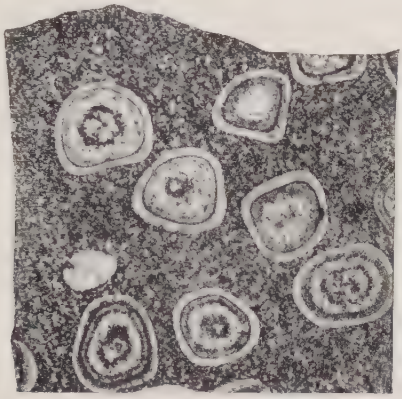

FIG. 123.—Orbicular diorite. Santa Lucia di Tallano, Corsica. (Prof. Dr. Öbbeke, photo.)

larger phenocrysts stand out from a denser groundmass (Fig. 122). Further, there are *spheroidal* (centric) textures in both granular and glassy rocks. In the former the spherules usually consist of

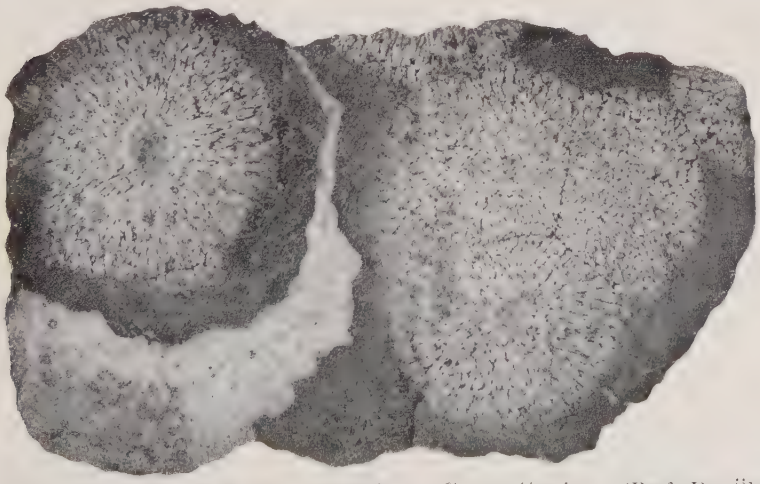

FIG. 124.—Quartz-porphyry with spherulites. Curzo, Corsica. (Prof. Dr. Öbbeke, photo.)

concentric light and dark shells (Fig. 123), in the latter of radial aggregates, as in spherulites (Fig. 124) and lithophysae. A regular or *pegmatitic* intergrowth of quartz and feldspar, called

graphic granite, may also be distinctly visible megascopically (Fig. 125).

Sedimentary rocks are typically *bedded* rocks. They may be

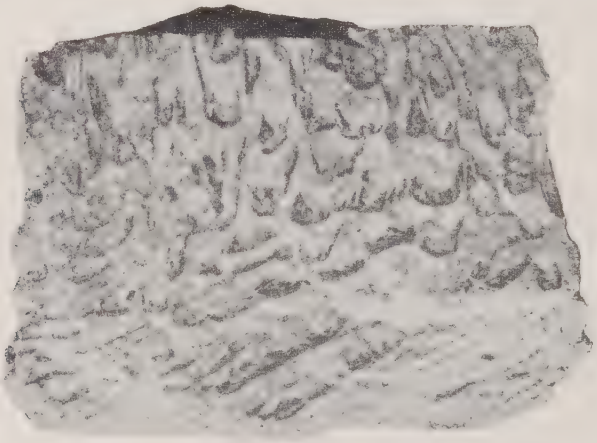

FIG. 125.—Graphic granite. Jekaterinburg, Urals.

perfectly or imperfectly schistose, thin- or thick-bedded, or platy, and in some cases, for example in limestones, they may even have as haphazard and massive a texture as normal igneous rocks. Schistosity parallel to the bedding is usually wavy rather than

FIG. 126.—Ripple-marked sandstone. Unterschönmattenwaag, Odenwald. (Prof. Dr. Klemm, photo.)

plane, but these irregularities are not always secondary. In many cases they are primary, as in ripple-marked sandstone (Fig. 126). In other places the original bedding-planes have been greatly altered by later displacements, and folding so intense that

the crests and troughs are now very narrow (Fig. 127) is common. Where alumina-poor rocks have been strongly folded, cross-fractures of many kinds are developed, and these are filled in part by plastic rock-material, in part by new deposits of quartz or feldspar. Furthermore, a fine crinkling at right angles to the coarser folds is developed, especially in the outer contact-zonès of plutonic rocks.

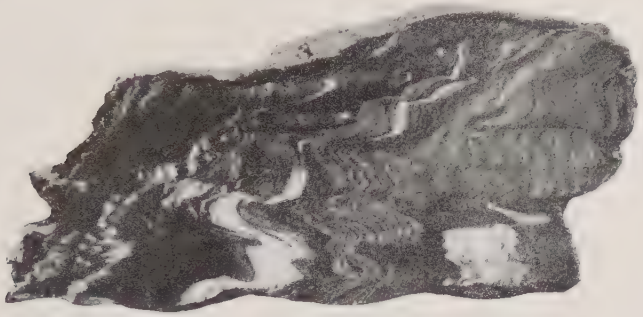

Fig. 127.—Folded schist. Alpe Puntaiglas, Switzerland.

Sedimentary rocks may consist chiefly of coarse quartz, and have a coarse clastic texture, a medium grain as in sandstones, or a fine grain as in argillites. Most normal limestones are dense, though some are cellular, and a cavernous development is found in dolomite. Amygdaloidal or kidney limestone is one in which the

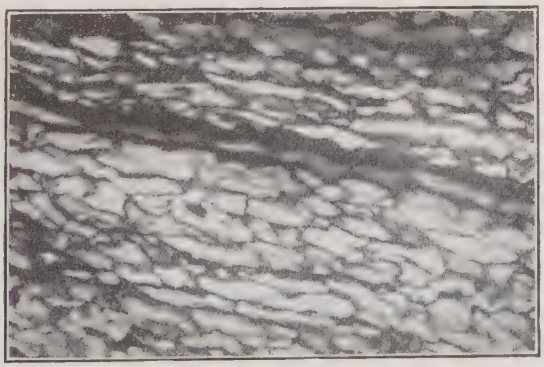

Fig. 128.—"Kidney" marble. Campane Valley, Pyrences.

calcite occurs in small, almond-shaped grains surrounded by a network of a clay-like substance (Fig. 128); where the calcite is dissolved out, these rocks have a porous, sponge-like surface.

Internal Textures.—That physico-chemical processes were active in the formation of a rock is shown by the mutual relationships

between the individual constituents as they appear in the textures. The broad relationships may be recognized megascopically in many cases, but a detailed study is only possible by the use of a microscope. The determination of the internal texture is only a little less important than the determination of the rock-forming minerals themselves.

If the relations between the textures of rocks and the processes of their formation can be determined in every detail, a most important step forward will have been made in the knowledge of geochemical processes in general. At the present time the following facts, based upon observations, may be stated:

When typically developed, three, sharply-contrasting types of textures may be distinguished. Two of these types belong to rocks in which the authigenic constituents greatly predominate, namely the crystalline rocks. In the third type, embracing the clastic or sedimentary rocks, the constituents are chiefly allothigenic. The two groups of crystalline rocks are (1) igneous, and (2) contact-rocks and the crystalline schists. The former are differentiated by the fact that the sequence of crystallization of the different minerals usually can be easily recognized, by a characteristic interlocking of the constituents, by the relative scarcity of inclusions in the minerals, and by a decided uniformity of all their characteristics. The second group of crystalline rocks, including contact-rocks and the so-called crystalline schists which are identical with them, are not uniform in appearance. The minerals are irregular in distribution and development, they are rich in inclusions, and there is no determinable sequence of crystallization. Finally, some contact-rocks clearly show remnants of a different, primary texture, partially obliterated by the recrystallization. This is the *palimpsest* texture.

Internal Textures of Igneous Rocks.—The textures of granular igneous rocks (Pl. II) clearly show that the mobility of the melts during crystallization must have been considerable, although it varied greatly in degree in different rocks. Igneous rocks, in the main, are homogeneous and uniform, and inhomogeneities such as schlieren, are generally the results of differentiation in the magma.

On account of the mobility of the molecules during crystallization, the constituents, in many cases, were able to unite to form large, homogeneous individuals. The boundaries of these crystals,

and various other features, make it possible to read the history of the solidification of the magma.

The constituents of igneous magmas crystallize according to the laws of separation from mixed solutions. Since these laws depend upon the external physical relationships on the one hand, and upon the mutual proportions of the dissolved substances on the other, igneous rocks necessarily show a variety of textures, all characteristic, and, where typically developed, any one of them a proof of the igneous origin of the rock.

Where the crystallization of a rock proceeded to its conclusion uniformly and without change of physical conditions, the sequence of crystallization also was entirely uniform; and the texture clearly shows how the melt, in the course of the separation, gradually became less complex. Finally, in the last stage of the solidification, the melt consisted of but a single mineral or of an eutectic mixture of two minerals, and this solidified as a mesostasis (Gr. μέσος, between, στάσις, position) between the minerals previously crystallized. These relationships may be seen distinctly in Figs. 1, 2, and 6, Pl. II. The mesostasis in Fig. 1 is quartz, in Fig. 6 augite, and in Fig. 3 a eutectic mixture of quartz and feldspar developed as micropegmatite. Rosenbusch[1] calls such textures *hypidiomorphic-granular* (Gr. ὑπό, nearly, ἴδιος, own, μορφή, form).

The principal textural varieties of these uniformly developed *granular* and *holocrystalline* (Gr. ὅλος, entirely) rocks are as follows. The *granitic* texture (Pl. II, Fig.1) is one in which the dark constituents show more or less distinct crystal boundaries against the feldspars, and these, in turn, show crystal boundaries against the quartz. Further, it may be seen that the less complex orthoclase separated later than the more complex plagioclase. The periods of separation of the individual constituents, however, do not always follow one after the other, but usually overlap. The crystallographic development of the individual constituents, therefore, is rarely so complete as that which is characteristic for the plagioclase and orthoclase in the *monzonitic* texture (Pl. II, Fig. 4).

The normal sequence of crystallization in a granite is shown graphically in Fig. 129, in which the abscissæ represent the duration of growth of the individual constituents. The minor accessories, such as apatite, zircon, etc., which occur in almost all rocks in very small amounts, are always the first products of separation (I), and their period of crystallization is usually completed when that of the chief constituents of the rock begins. Then follows biotite (II), whose period is not yet completed when the crystallization of the plagioclase (III) begins. The latter overlaps the development period of orthoclase (IV) and quartz (V), and the orthoclase overlaps the quartz. Such crystallization, in its main features, is characteristic for most granites, syenites, monzonites, quartz-diorites, and diorites.

[1] Rohrbach's term *automorphic* (1886) has priority over Rosenbusch's *idiomorphic* (1887). *J.*

The appearance of aplites and of most two-mica-granites is somewhat abnormal, for the crystallization begins with the separation of quartz and usually ends with the production of micropegmatite as interstitial material (Figs. 2 and 3, Pl. II). This texture is called *granulitic* (Fr. *granulite*, two-mica-granite) or *aplitic*. It has been incorrectly named *panidiomorphic* (Gr. πᾶν, all), but such a texture is inconceivable in a compact, crystalline rock. If micropegmatite predominates as interstitial material, the texture is *micropegmatitic*.

The above characteristic sequence of separation gradually disappears in the rocks from diorite to those that are more basic. Thus in the *gabbroic* texture (Pl. II, Fig. 5) the constituents are equally developed, showing that they crystallized nearly simultaneously. This *allotriomorphic*[1] (Gr. ἀλλοτριος, foreign) texture gives place, in rocks containing still more of the basic constituents, to the *ophitic* texture (Pl. II, Fig. 6) of traps and diabases, in which the colored minerals form the mesostasis. With a still further decrease in the amount of feldspar, this texture also is lost, and the feldspar-poor picrites, and especially the feldspar-free peridotites, again have an allotriomorphic-granular texture. The intergrowths of pyroxene and olivine in the peridotites, in some cases, show a *poikilitic* (Gr. ποικίλος, spotted) or an *implication* texture (Lat. *implicare*, to fold in), presumably representing a eutectic mixture.

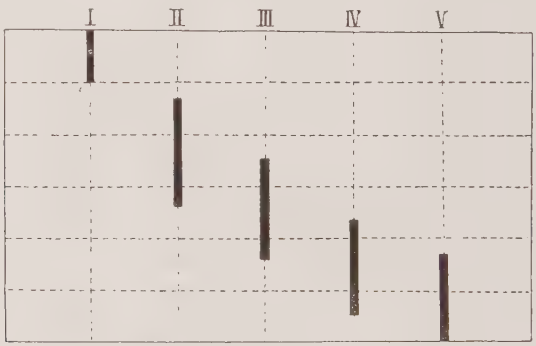

FIG. 129.—Sequence of crystallization in granite.

If the physical conditions were altered during any stage of the crystallization of a rock, a hiatus occurred in the separation. This is characteristically seen in extrusive rocks in which larger *intratelluric* (Lat. *intra*, within, *tellus*, the earth) *phenocrysts* (Gr. φαίνω show) stand out from a finer groundmass and produce the *porphyritic* texture (Pl. III, Fig. 1). When these rocks have a completely crystalline groundmass they are also called *holocrystalline-porphyritic* (Gr. ὅλος, entirely), in contrast to *hypocrystalline-porphyritic*, in which a glassy basis is present.

There is great variety in the textures of groundmasses, especially in silicic rocks. The groundmass in Fig. 1, Pl. III is *microgranitic*, that in Fig. 2 is *glassy* or *vitrophyric* (Lat. *vitrum*, glass) and has a fluidal *eutaxitic* (Gr. εὐταξία, good order) development. Fig. 3 shows the *spherulitic* (Gr. σφαῖρα, sphere) or *granophyric* (Lat. *granum*, grain) texture of quartz-porphyry. Between these textures there are all possible transitions. In many of them the crystalline condition cannot be proved with certainty, and such rocks are called *felsophyric* or *microfelsitic* quartz-porphyries.

A fluidal arrangement of small feldspar laths is characteristic for the groundmass of the *trachytic* texture (Pl. III, Fig. 4). Where feldspar individuals of trachyte are

[1] *Xenomorphic*, ROHRBACH (1886), *allotrimorphic*, ROSENBUSCH (1887).

more equidimensional in outline and less uniformly distributed, the texture is *orthophyric*. In some andesites there is a more or less fluidal arrangement of the plagioclase laths of the groundmass; this is the *pilotaxitic* (Gr. πίλος, felt, τάξις, order) texture. In others these laths are more irregular in their distribution, as in the *andesitic* or *hyalopilitic* (Gr. ὕαλος, glass) texture shown in Fig. 5, Pl. III.

Among the basic melaphyres there occurs a texture analogous to the ophitic, namely the *intersertal* (Fig. 6, Pl. III). In this texture the interstices between the feldspar laths are filled with glass. In rocks of the basalt group, which are still poorer in feldspar, the constituents of the groundmass form a felty aggregate of microlites which can hardly be resolved by the microscope. This is the *microlitic* texture. In the last two cases the true porphyritic character, that is the occurrence of two generations of the same mineral separated by a time interval, may be inconspicuous.

Internal Textures of Contact-rocks and Crystalline Schists.—Several very different textures occur among the rocks which are included under the name of crystalline schists. Schlieren granites, diorites, or gabbros generally have the same textures as the corresponding normal rocks, but in another group, mechanical textures predominate and in many cases nearly conceal the original character. The textures of the metamorphic schists differ entirely from those found in igneous rocks. They were long ago recognized as being the same as those characteristic at contacts, and this identity of textures shows that the physico-chemical processes which were active during their formation were also identical.

A microscopic study of the textures of metamorphic schists, and contact and igneous rocks shows that only in the latter is there a characteristic sequence of separation of the minerals. Although individual constituents may stand out from the groundmass on account of greater size or more perfect crystal form, careful study shows that all of the minerals of the apparent groundmass occur also as inclusions in the larger crystals. The latter, therefore, cannot be older. Such textures are called *pseudoporphyritic*. In the *knoten* texture the larger crystals appear megascopically in the form of knots upon fracture-planes, in the *garben* texture they occur in sheaf-like forms.

If the peculiarities of the textures of contact-rocks and crystalline schists be examined carefully, numerous details will be found which show that the molecules were much less mobile during the crystallization of these rocks than they were in igneous magmas. But at the same time it is certain that the recrystallization did not take place when the rocks were in a solid state, as believed by Rosenbusch.

In the more important typical occurrences of contact-rocks and metamorphic schists, the materials for the different constituents clearly came from rather distant sources. The condition of the rock substance, however, was too viscous to permit the formation of pure crystals, consequently there are usually many inclusions, especially in the larger phenocrysts. This gives rise to the *sieve* texture (Pl. IV,

Fig. 1). In many cases intimately intergrown aggregates of different minerals occur instead of simple homogeneous crystals, and these may be so dense that they are not transparent except in very thin sections (Fig. 2, Pl. IV).

A further proof of the slight mobility of the molecules is the fact that remnants of the original texture are preserved in places (*palimpsest* texture), and may even appear distinctly to the unaided eye, as in the *porphyritic* (Fig. 83) and *ophitic* textures of innumerable greenstone-schists. Well-preserved fossils (Fig. 130) in recrystallized sediments may also show that there has been but slight movement. In other cases the original texture cannot be seen without the microscope, as in the *helizitic* texture (Gr. ἕλιξ, spiral: Pl. IV, Fig. 3), in which bands and strings of inclusions, representing the original schistosity of the rock, cut across the newly formed constituents of the altered rock.

In the *mosaic* texture (Pl. IV, Fig. 4), which likewise is very characteristic of these rocks, the individual grains lie adjacent to each other like irregular paving-blocks, and meet with rather straight contacts. Similar textures are shown in Fig. 1, Pl. V, and Fig. 1, Pl. VI. In Fig. 2, Pl. V, and Fig. 2, Pl. VI, the meeting-lines between the grains are very irregular or toothed. This *sutured* texture, in many cases, occurs in

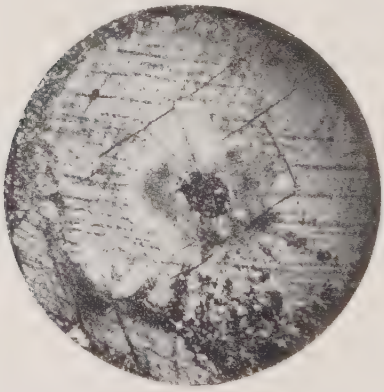

Fig. 130.—Crinoid stem in coarse marble. Bayumkol Valley, Tien-Schan.

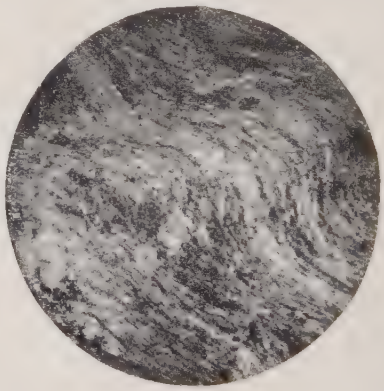

Fig. 131.—Quartz-phyllite. Sunk, Steiermark. Shows folded sericite films.

association with the mosaic texture. It is especially striking in itacolumite (Pl. V, Fig. 3) in which the irregular quartz grains are not cemented and the rock is flexible.

All the micaceous minerals of rocks which recrystallized under high pressure occur in parallel planes (Fig. 131). This is the *crystallization-schistosity* of Becke. Wherever a larger mica crystal lies across the direction of these planes, that is with its base parallel to the direction of the pressure, it shows unusually poor outlines and a thick-tabular development (Pl. IV, Fig. 5).

Becke gave innumerable new names to the textures of the metamorphic schists in an attempt to separate them from those of contact-rocks. He compared the crystallization from a viscous mass to sprouting, and called all rocks which originated in this manner *crystalloblastic* (Gr. βλαστὸς sprout). He distinguished further: *granoblastic* or *cyclopic* textures, corresponding to the mosaic textures of igneous rocks, *lepidoblastic* corresponding to scaly, *nematoblastic* = fibrous, *homöoblastic* = equi-granular, *porphyroblastic* = pseudo-porphyritic, *diablastic* = sieve texture, *poikiloblastic* = helizitic, *idioblastic* = automorphic, *xenoblastic* = xenomorphic. *Blasto granitic* was applied to rocks having a palimpsest texture with an underlying veiled-granitic

texture, and in an analogous manner *blastophitic, blastoporphyritic, blastopsephitic, blastopsammitic,* etc., were used. The mortar or murbruk texture, which originated in brecciation, was called *porphyroclastic.*

Internal Textures of Sedimentary Rocks.—Three different kinds of constituents, clastic, organic, and authigenic, influence the textures of sedimentary rocks. The clastic constituents are most characteristic, and the term *pelite, psammite,* or *psephite* indicate the size of the grains of which they are composed.

Besides minute quartz splinters and occasional fragments of purely accidental constituents, there is usually little to see in typical pelites, even under strong magnification. On the other hand, the clastic nature of the psammites is very distinct. The æolian or alluvial origin of many of them may be shown by the fact that the chief constituent, quartz, occurs in rounded grains in the former (Pl. V, Fig. 6) and in angular fragments in the latter (Pl. V, Fig. 5). The cement also in many cases occurs in very characteristic forms, even though partially modified by diagenic processes. For example, the water-clear quartz cement in the rock shown in Pl. V, Fig. 6 is a secondary growth around the originally rounded, dark-bordered sand grains.

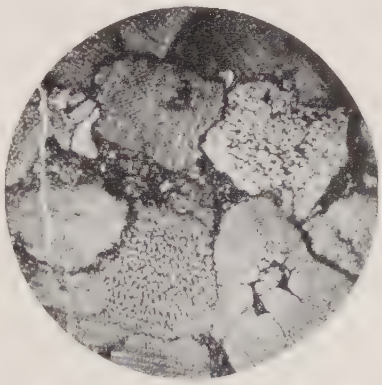

FIG. 132.—Crinoid limestone with grating texture. Vilstal, Pfronten, Algäu.

The second class of sediments, such as crinoid limestones (Fig. 132), owe their textures to the preserved skeletal parts of organisms. As was shown above, different kinds of skeletons possess different degrees of durability; siliceous skeletons being least, and bones most durable. Calcareous fossils may be easily separated into two groups. One of these is based upon the character of the inorganic material of the skeletons, whether calcite or conchite. Original conchite is never preserved, for it is altered by diagenic processes to granular calcite. On the other hand, many calcite fossils preserve their structures, especially if they were originally coarsely crystalline, as are the skeletons of echinoderms, while fine-fibrous, ray-like foraminifera rarely preserve it. The second group of microscopic structures of calcareous skeletons depends

upon the distribution of the original organic material in them. The structure is distinctly brought out by the diagenic alteration of this material to carbonaceous matter, for example in the grating structure of crinoids (Fig. 132).

The third group of constituents which may influence the structure of sediments differs from the other two in being authigenic. These constituents originated either by direct chemical sedimentation, as in gypsum and rock-salt deposits, or by diagenic processes. In the former case they may be quite coarsely crystalline, in the latter, especially in carbonate- and silicate-rocks, they may consist of fine-grained crystalline aggregates. Even when the constituents are nearly submicroscopic in size, they may be distinctly recognized as authigenic.

Finally, the oolitic texture is typical in many carbonate-rocks. In these the original radial-concentric development may be distinctly preserved (Fig. 5, Pl. VI), but more commonly a diagenic recrystallization has produced a granular aggregate of calcite (Fig. 6, Pl. VI).

It may be pointed out in conclusion that secondary fillings in fissures and cracks, or infiltrations along bedding- and schistosity-planes, may produce confusion in the microscopic examination of the textures of sedimentary rocks. In many cases these can be recognized in the thin section only by their much more distinct crystalline development.

Mechanical Textures.—All rock-textures modified by the action of orogenic processes are included under the term mechanical textures. They may be seen megascopically in many cases, most distinctly in folded bedded-rocks and in transversely-schistose argillites. The degree of consolidation of sediments, and the numerous fissures, veins, and pressure-sutures of carbonate-rocks, all indicate mechanical action. Mechanical alterations may be observed even with the unaided eye in true crystalline rocks, for many coarse-grained marbles are mashed to wax-like, dense aggregates, and the crushed quartz of granitic rocks takes on a sand-like appearance.

The action of mechanical forces appears much more variable and distinct in the internal structures of rocks than in the external. In limestones the most common form of alteration is the destruction of the organic texture, but there are many other kinds. Various minerals behave very differently toward pressure. For example,

mica may be greatly bent without being broken (Pl. IV, Fig. 6), while quartz shows distinctly the slightest trace of such action by its undulatory extinction in polarized light. With further fragmentation the quartz is cut by transverse and longitudinal cracks which are filled with grains produced by the mechanical movement, and between these cracks coarse remnants of the original crystals remain. This is the *mortar* or *murbruk* texture (Pl. V, Fig. 4). Olivine acts in much the same way.

The amount of bending or breaking of certain minerals serves as a scale for the measurement of the degree of mechanical action which the rocks have suffered. Intermediate between the flexible mica and the brittle quartz stand the other minerals. Diopside and hornblende may still be bent, although the latter may be somewhat displaced along cleavage lines, so that a cross-section resembles parquetry (Fig. 133). If these textural features were produced by mechanical processes which were active during the solidification of the rock they are called *protoclastic* (Gr. πρῶτος, first, κλάω, to break), if they originated after the rock solidified they are called *cataclastic* (Gr. κατά, after).

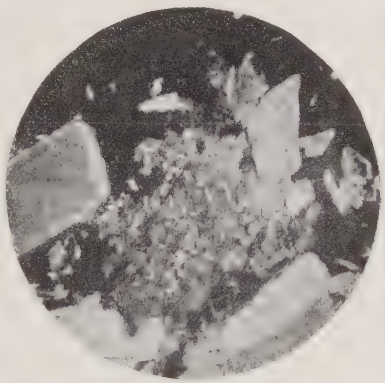

Fig. 133.—Crushed actinolite in serpentine. Stubachtal, Salzburg.

Calcite is of especial interest, not only on account of its wide distribution but also because such thorough experiments have been made upon it. It has been found that at ordinary temperatures calcite quite readily becomes cataclastic (Pl. VI, Fig. 3), and then resembles mashed quartz. At a temperature of several hundred degrees, however, it has considerable plasticity, due partially to gliding and the development of fine twinning-lamellæ, partially to direct bending of the lamellæ themselves. In numerous granular limestones a re-formation has taken place along twinning-lamellæ of the calcite but the mineral itself shows no signs of fracturing (Pl. VI, Fig. 4). Such rocks, therefore, may be assumed to have been under the action of mechanical forces in the presence of heat.

All of the above characters are due to lateral pressure acting under an enormous overlying load. With a sudden cessation of the stress, however, as by faulting, such minerals as calcite, mica, etc., which are highly plastic under pressure, will be completely fractured. Under such conditions, on account of the friction in the fault-clefts or slipping-planes, the whole rock may be uniformly reduced to a grit-breccia, or there may be formed a fine, porous material containing more or less abraded or striated blocks of the country-rock resembling glacial boulders, or compact rocks may be produced with pronounced flaser structures and showing fragments of the original rock as eyes in a brecciated schistose groundmass. In addition, many new minerals, chiefly mica-like, are formed by circulating juvenile solutions. In many cases the breaking up has gone so far that only fine dust remains, as in the clay-schist dikes of the Harz, or there is formed a uniform, dense, schistose rock like the Pfahl schist, whose origin from granite would never be suspected from its present appearance. Intense crushing also occurs at the base of great overthrust faults, and materials from the underlying

rocks, planed off by the movement, are mingled and kneaded together, and finally consolidated as dense rocks with a peculiar *kneaded* texture (Fig. 103). All of these rocks produced by brecciation are grouped together as *mylonites* (Gr. μύλη, mill).

Inclusions, Concretions, and Secretions.—There still remain to be mentioned inclusions, concretions, and secretions. Inclusions embrace, primarily, the foreign

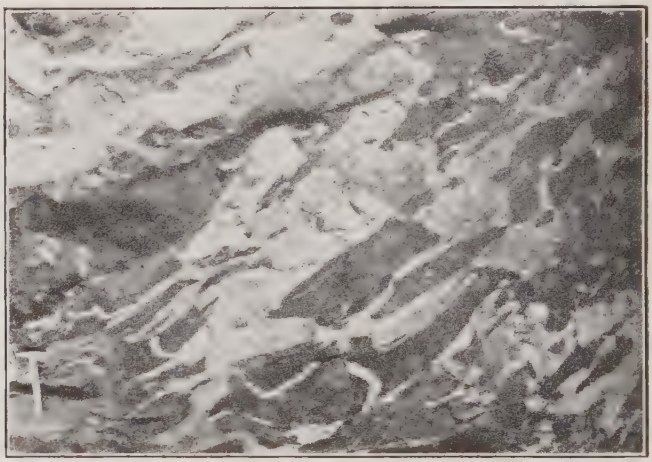

FIG. 134.—Contact-breccia. Gabbro-diorite intruded by granite. Schönberg along the Bergstrasse. (Prof. Dr. Klemm, photo.)

rock- or mineral-fragments which are contained in igneous rocks. In some cases they have preserved their original fragmental form, in others they have been partially fused or metamorphosed by the action of the molten magma or even injected with the

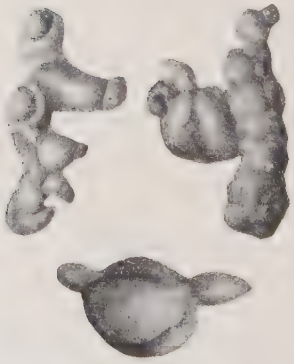

FIG. 135.—Loess kindl. Uttenhofen, Rheinpfalz. The lower example is very sandy.

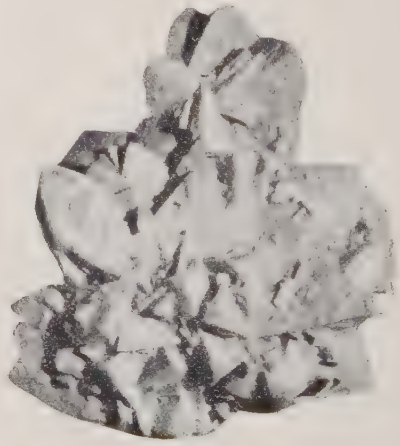

FIG. 136.—Crystallized sandstone. Fontainebleau near Paris.

igneous material. When the inclusions are *endogenic* (Gr. ἔνδον, within), as in many lamprophyres, they usually have sharply defined borders and represent fragments of

material which solidified in the magma itself in the bowels of the earth. The most important of such inclusions are the olivine nodules so common in basalts.

A second group of inclusions are *exogenic* (Gr. ἔξω, out), and consist of fragments of the country-rock, torn loose by the igneous magma. In many plutonic rocks these have been so far assimilated that they stand out from the otherwise homogeneous rocks only as poorly defined spots, the so-called basic inclusions. Gneiss inclusions in granite may have preserved their original schistose character and have become filled with injections of the igneous rock. Inclusions are especially numerous in small dikes and in the border-zones of large intusives where they form contact-breccias (Fig. 134).

A great variety of exogenic inclusions occur in volcanic tuffs. They consist of normal contact-rocks, which were clearly altered before the magma reached the surface, and fragments of the country-rocks through which the rising magma passed. The latter are usually fritted. Especially interesting to the mineral collector are the

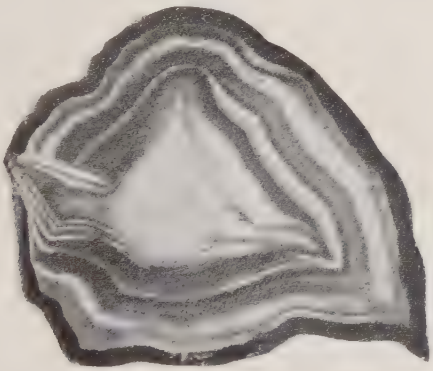

FIG. 137.—Agate, showing conduit. Oberstein a. N.

inclusions and ejectamenta of sodic rocks, which in many cases are entirely saturated by the constituents of the magma.

Concretions (Lat. *concretus*, grown together) are concentrations of certain constituents in sediments. In some cases they originated during the rock formation, in others by later processes. Here belong the clay-pockets of sandstones, the much-fissured, lens-like septaria of clays, nests of gypsum, pyrite, marcasite, and siderite in marls and argillites, of flint in chalk, and of menilite in the siliceous schists; also loess-kindl (Fig. 135) representing calcareous concretions, sand-filled calcite-clusters in the so-called crystallized sandstone (Fig. 136), knots and bands of hornstone and carnelian in limestones of different formations, and finally masses of limonite, phosphorite, celestite, etc.

Secretions (Lat. *secretus*, separated), or more correctly infiltrations, include all cavity-fillings in rocks. Among these are amygdules and geodes of calcite, zeolites, and agate (Fig. 137) in vesicules of igneous rocks, veins of quartz and calcite in all kinds of rocks, and all mineral aggregates in cavities of any kind. The material in all cases was brought in from external sources.

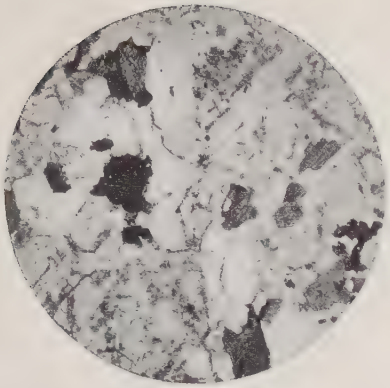

FIG. 1.—Granitic texture. (After Berwerth.) The dark constituents show distinct boundaries against the light. Quartz (the lightest mineral in the figure) was the last mineral to crystallize. It fills the interstices between the earlier constituents. Ordinary light.

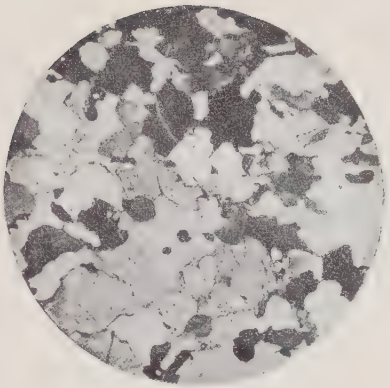

FIG. 2.—Granulitic texture. Quartz shows distinct boundaries against the remaining constituents. Polarized light.

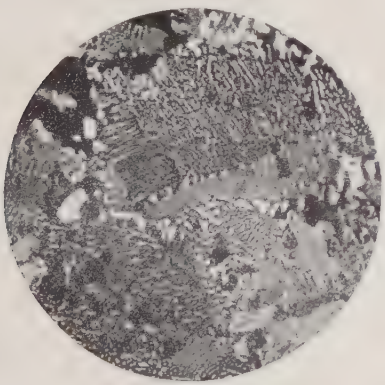

FIG. 3.—Micropegmatitic texture. The eutectic mixture of orthoclase and quartz in graphic intergrowth was the last product of crystallization. Polarized light.

FIG. 4.—Monzonite texture. The orthoclase fills the interstices between the plagioclase laths. Polarized light.

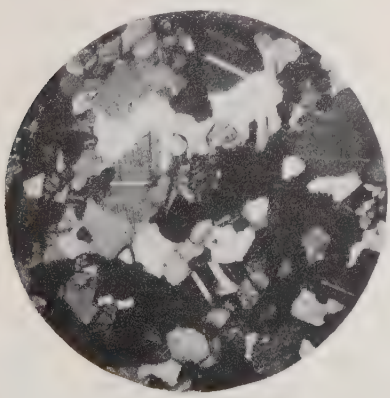

FIG. 5.—Gabbro texture. Irregular, granular arrangement. Polarized light.

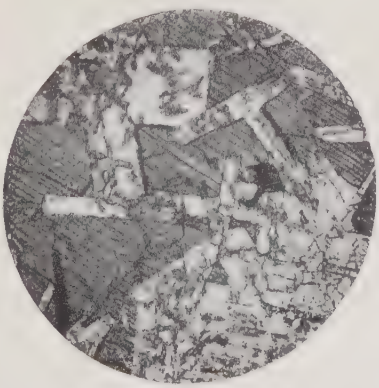

FIG. 6.—Ophitic texture. Large augite individuals fill the spaces between plagioclase laths. Ordinary light.

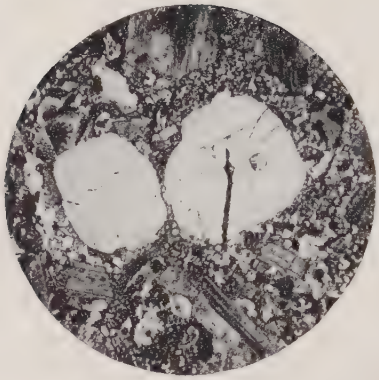

FIG. 1.—Porphyritic texture. (After Berwerth.) The groundmass is micro-granitic, and in this lie large phenocrysts of quartz and feldspar. Polarized light.

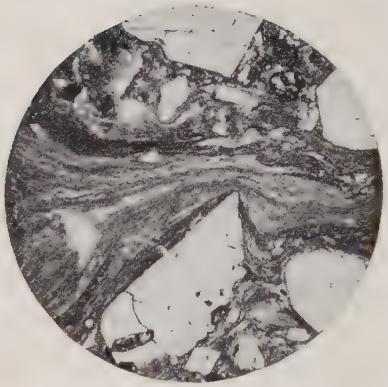

FIG. 2.—Eutaxitic texture. The groundmass shows distinct fluidal texture. Ordinary light.

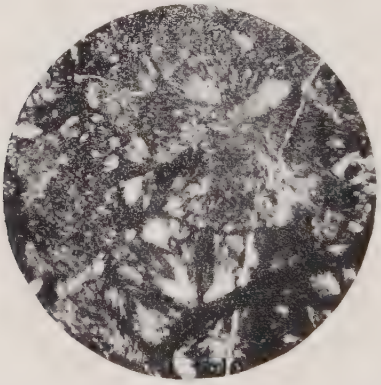

FIG. 3.—Spherulitic texture. The groundmass consists predominantly of radially arranged quartz-feldspar aggregates. Polarized light.

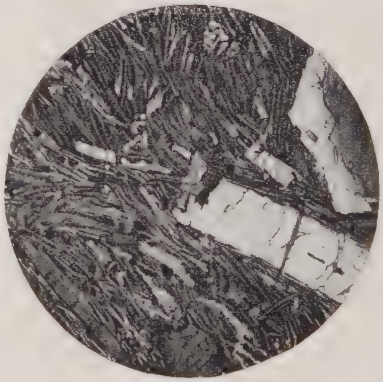

FIG. 4.—Trachytic texture. (After Berwerth.) Feldspar microlites are arranged in flow-lines around the phenocrysts. Polarized light.

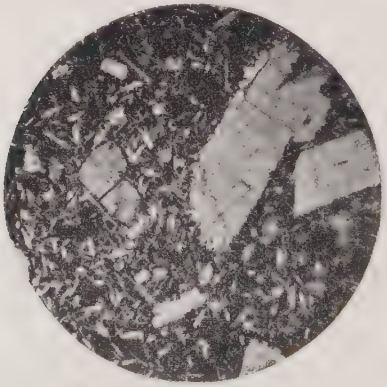

FIG. 5.—Hyalopilitic texture. The groundmass is rich in glass, and contains unoriented microlites of plagioclase and augite. Ordinary light.

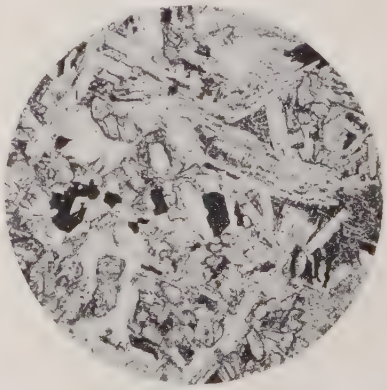

FIG. 6.—Intersertal texture. (After Berwerth.) The last remnant of the magma solidified as a microlite-filled glass. It fills the interstices between the remaining constituents. Ordinary light.

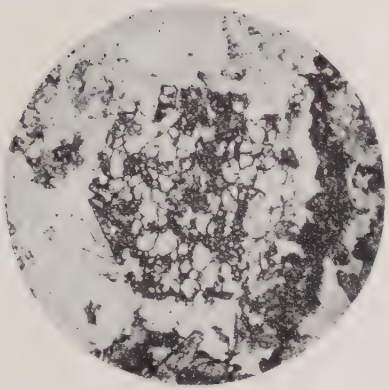

FIG. 1.—Sieve texture. A garnet crystal with poor boundaries is filled with inclusions of the other constituents. Ordinary light.

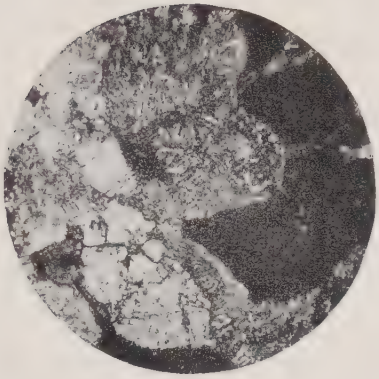

FIG. 2.—Implication texture. Aggregate of pyroxene and plagioclase. Polarized light.

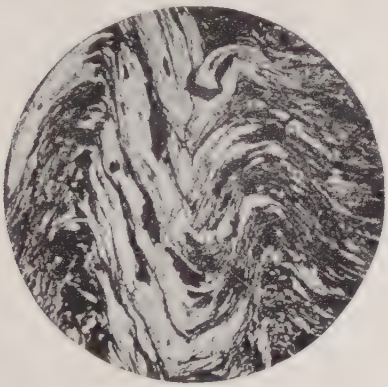

FIG. 3.—Helizitic texture. Biotite, sillimanite, and ilmenite crystals, arranged parallel to the original bedding, intersect a crystal of cordierite which takes up the greater part of the field of view. Polarized light.

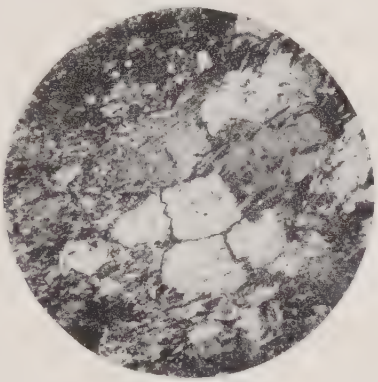

FIG. 4.—Mosaic texture. The albite crystals are arranged as in a mosaic. Polarized light.

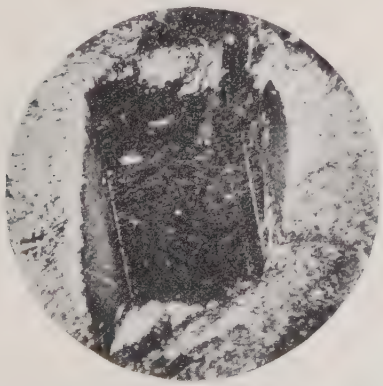

FIG. 5.—Biolite with its long direction at right angles to the cleavage of the rock. Ordinary light.

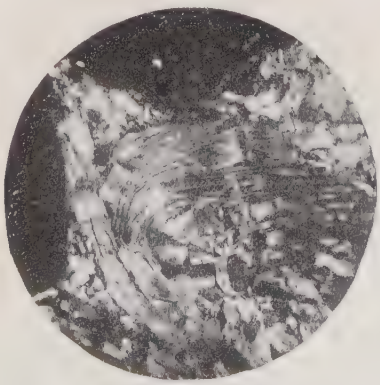

FIG. 6.—Bent biotite lamellæ. Though the mica is greatly bent, it shows no breaks. Polarized light.

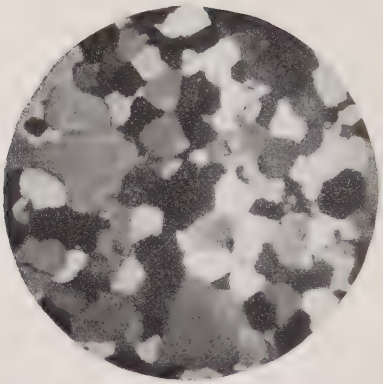

FIG. 1.—Mosaic texture. Quartz grains with rather plane contacts. Polarized light.

FIG. 2.—Sutured texture. The quartz individuals interlock and are firmly united. Polarized light.

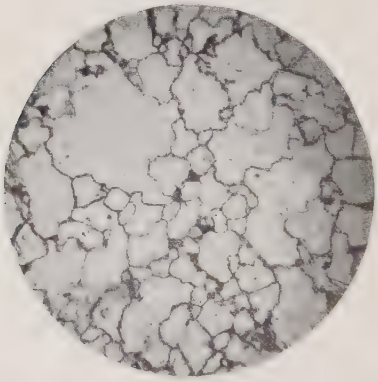

FIG. 3.—Sutured texture in itacolumite. The quartz individuals interlock but are not firmly united. Ordinary light.

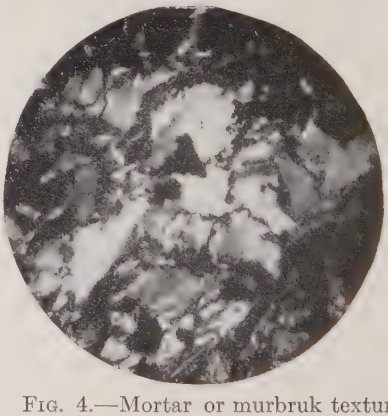

FIG. 4.—Mortar or murbruk texture. Shows fine quartz grains in fissures in quartz grains with undulatory extinction. Polarized light.

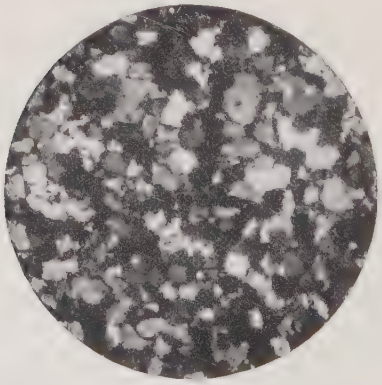

FIG. 5.—Clastic texture. Angular quartz grains, clearly alluvial, in a dense, clay-like cement. Polarized light.

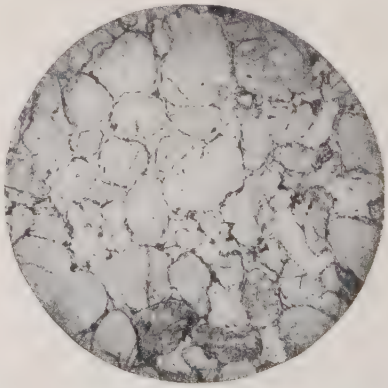

FIG. 6.—Clastic texture. Rounded quartz grains, clearly aeolian, with rims of secondary quartz. Ordinary light.

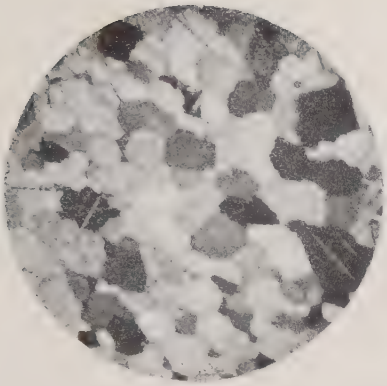

FIG. 1.—Mosaic texture. Calcite crystals with rather plane contacts. Polarized light.

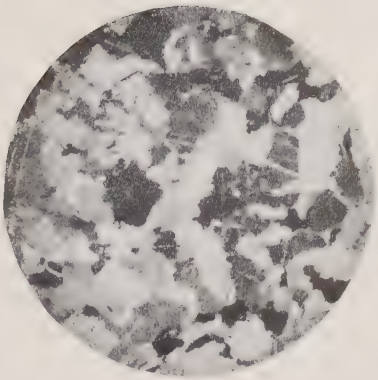

FIG. 2.—Sutured texture. The calcite grains interlock. Polarized light.

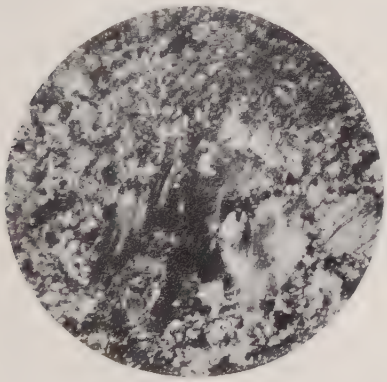

FIG. 3.—Cataclastic texture. Fine calcite aggregates between strained remnants of larger grains of calcite. Polarized light.

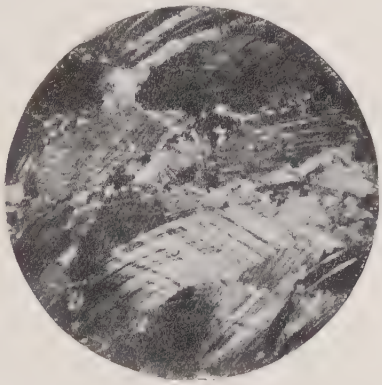

FIG. 4.—Mechanical texture. The twinning lamellæ of the calcite are bent yet the mineral is not broken. Ordinary light.

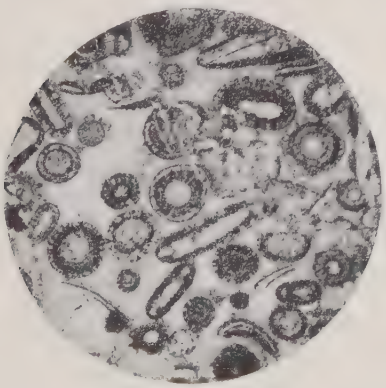

FIG. 5.—Oolitic texture. Shows the original radial and concentric arrangement within the individual spherules. Polarized light.

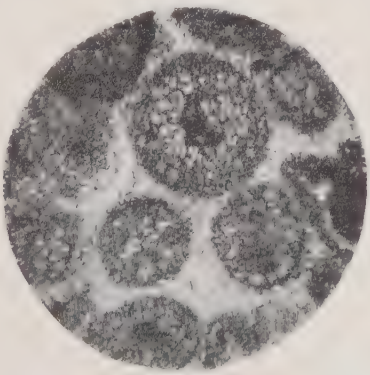

FIG. 6.—Oolitic texture. The spherules have been altered by diagenesis to a granular aggregate. Polarized light.

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